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The Study of the PHYSICAL WORLD

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HYSICAL WORLD

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Preface

THIS TEXT, now in its second edition, is the product of fifteen years of experience and constant experimentation in the presentation of a survey course in physical science as a part of a general education program. The authors and others who participated in this development felt the need for a text which would be compatible with the aims of such a course and at the same time be within the intellectual grasp of the average college student. Results with a large number of students were therefore measured and carefully analyzed, and the experiences of many college staff members were drawn upon both for the selection of subject matter and its manner of presentation.

The importance of science in general education has long been recognized. Benjamin Franklin,[1] in discussing the curriculum of the Philadelphia Academy — later the University of Pennsylvania — stated that the students should study "histories of science" and that science should be taught to all future citizens for its functional values. But it is neither feasible nor desirable to require the general student to take the more specialized laboratory courses. For in these courses, with their specialized techniques and involved formulae, he can neither view the whole picture of science nor grasp, save by haphazard implication, the relationship of a particular course to the general scheme. Today science is a vital part of our national and international life and culture. Its achievements, both intellectual and philosophical on the one hand and practical and utilitarian on the other, have been instrumental in lifting some of the people of the world from the superstition, dogmatism, and drudgery of the past. Yet despite the nobility of the aim of science — the pursuit of knowledge and its constructive use for the improvement of man's lot — the advances of science are not always intelligently employed. Science has made war more costly, more widespread, and more horrible. It has made us more mindful of the contrasts between knowledge and ignorance, wealth and poverty, civilization and savagery. In the wake of each discovery or development come new social and economic problems. People must become more keenly aware of these problems. One objective of this course is to enable the student to

[1] Benjamin Franklin, *Writings* (Smith Edition), vol. II, page 395. New York: The Macmillan Company, 1907.

comprehend and feel the greatness of science, yet to realize its shortcomings and its destructiveness when misused.

The authors have been pleased with the response by educators and scientists to the first edition of this work. Since the close of the war, a renewed interest in general education has become increasingly evident. The available texts that presumably cover the core material in the physical sciences in a program of general education follow many different patterns, from the purely descriptive type of course on the one hand to the narrowly analytical and mathematical approach within a single subject field on the other. The authors of this text have tried to give a unified approach to the study of the physical sciences without recourse to the artificial boundaries of the conventional subject field areas, retaining at the same time, in so far as possible, the rigor of the methods of science in the presentation of the course material. The book was planned with these general aims:

(1) To emphasize the significance of science in relation to modern life, its potentialities for good and for evil;

(2) To stress continually the methods of science, rather than the end products of scientific thinking, in the hope that its applications will thereby be greatly extended;

(3) To give students some special knowledge of modern science which will function in their own lives in a socially desirable manner.

It is acknowledged that these aims mean that many of the difficult topics in the pure sciences cannot be avoided, nor should there be an attempt to avoid the use of elementary mathematics. The factual material which is included is necessary to an adequate treatment of the relatively few basic principles of science which are presented. But there is still more material than can properly be presented during one college year, a condition which permits considerable flexibility in the presentation of the course and also permits better adaptation of the text to local teaching situations. At the same time, the additional material furnishes desirable reading for the inquiring student.

The principal changes in this edition include:

(1) Complete revision and expansion of the chapters dealing with the structure of matter, both as to the nuclear and extra-nuclear structures of atoms and including the important subject of nuclear energy;

(2) The condensation of the former chapters on fuels and foods into a single chapter on fuels;

(3) A complete revision of the section on weather;

(4) A thorough revision and simplification of the chapters on chemistry; and

(5) The inclusion of a number of significant recent scientific advances

As an aid to both student and teacher, complete summaries, study exercises, and detailed references for further readings are included in each chapter. Problems and study exercises, mostly of the objective type, ar

found to be helpful for tests and home assignments. It is not intended that the student mark these exercises in the book. The reading suggestions refer for the most part to authors who emphasize the social and philosophical significance of the various topics.

Credit for the improvement of the volume belongs primarily to those who have used it in their classes. The authors are especially anxious to acknowledge the suggestions of the following persons:

Doctor John R. Ball, Department of Geology, Northwestern University; Mr. Don Carroll, Illinois State Geological Survey; and Mr. Ross Rollins, Boston Geological Society.

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Doctor Theodore A. Ashford, The College of the University of Chicago.

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THE AUTHORS

The Study of the PHYSICAL WORLD

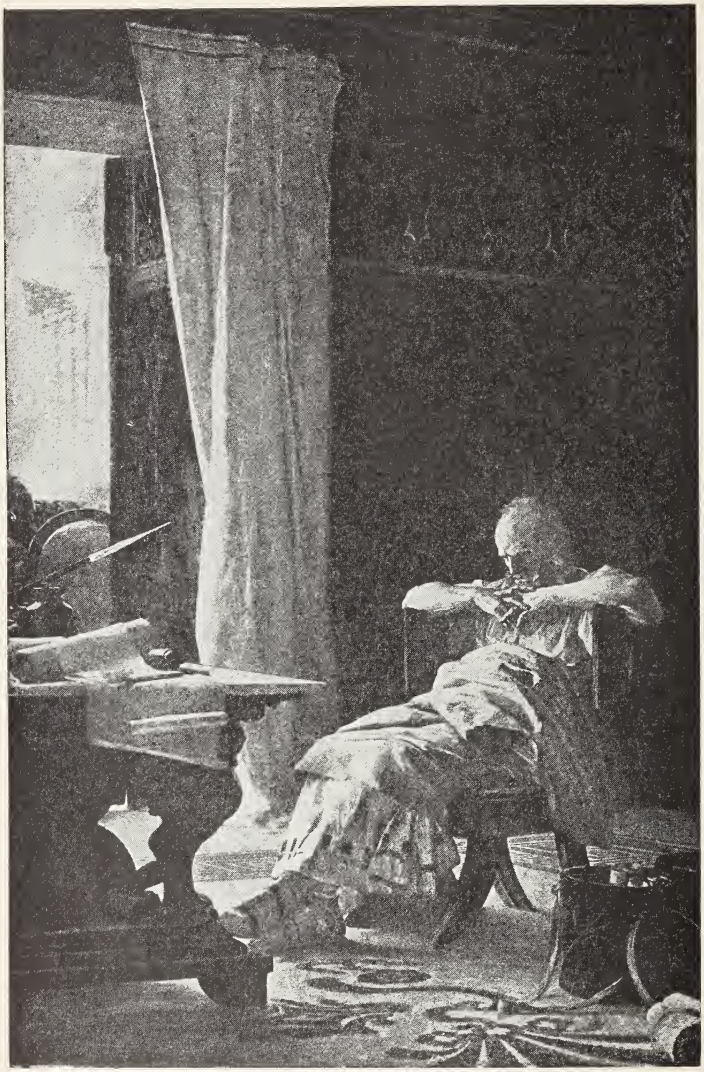


FIGURE 1. ARCHIMEDES, THE FIRST OF MODERNS, 287–212 B.C.

1

Prelude to Science

TOO MANY complacently accept the achievement of present-day science. It is only a few years since the atomic bomb brought unprecedented destruction. This was a surprise example of an end product of scientific thinking, terrible in its immediate applications and awful to contemplate as a future weapon of war. The difference between the methods used to obtain an atomic bomb and a new kitchen gadget is a matter of degree and not of kind. Both represent end products of scientific thinking — they are not science itself. Science is of the mind — subjective, not objective. The fundamental principles which made the atomic bomb possible were products of the human mind.

There are those who hold science responsible for the present chaotic condition of the world. But these critics should rather persuade mankind to think and act scientifically. As many former civilizations have collapsed, so our civilization can collapse unless people the world over come to understand the real significance of science as a method of thinking and an outlook on life.

Man is an animal. It may please some of us to say that man represents the highest form of animal life. Man's body mechanism, however, in certain respects is inferior to that of many animals. For example, he is weaker physically, has poorer eyesight, hearing, and sense of smell than many members of the animal kingdom. The average span of life of quite a number of animals exceeds the traditional "threescore years and ten" of the human. Many forms of animal life persist in environments where conditions of temperature make human life impossible. How then did man attain a position of dominance on the earth? The answer is both easy and difficult. The significant difference between man and lower animals is found in the greater brain capacity and higher intelligence of man. This has resulted, with the passage of time, in a great accumulation of knowledge, customs, and practices forming great cultures which have been transmitted from generation to generation and which have continually changed and improved to meet new conditions by the process of trial and error and by the process of reflective thinking. A culture is defined as a complex

whole which includes knowledge, belief, art, morals, law, custom, and any other skills or habits acquired by man as a member of society.

Man is what he is today because of his culture, a heritage from the past, and because he strives to evolve a better culture. The urge to improve causes progress. The story of the beginning of our modern western culture or civilization is for convenience divided into a number of stages: (1) Eolithic or Dawn Stone Age, (2) Paleolithic or Old Stone Age, (3) Neolithic or New Stone Age, (4) Bronze Age, and (5) the early cultures of Egypt and Mesopotamia. The essential element in the evolution of these various cultures was time. The Eolithic cultures existed about a million years ago; the Paleolithic about a hundred and fifty thousand years ago. The Neolithic cultures date back about fifteen thousand years ago, and the Bronze Age to about 4000 B.C.

It is natural to inquire why these cultures advanced so slowly, especially during the early stages of civilization. This slow progress was due principally to three reasons: (1) to the lack of a system of writing; (2) to the empirical method of obtaining new knowledge; and (3) to man's own attitude toward nature or his own environment.

Because of the lack of a system of writing, the advances of one generation could be passed on to the succeeding generation only by precept and example, often a very unreliable and uncertain process. Writing came into use in Egyptian civilization about 3000 B.C. J. H. Breasted, the great student of early Egyptian civilization, has emphasized the importance of this development in the words:

> The invention of writing and of a convenient system of records on paper has had a greater influence in uplifting the human race than any other achievement in the career of man. It was then and is now more important than all the battles ever fought and all the constitutions ever written.[1]

The empirical method of accumulating knowledge arose out of experience and continued to be the principal means of extending man's mental horizon until the emergence of the scientific method. Empirical knowledge depends for discovery upon fortunate observation. Thus, the superiority of copper or bronze over flint as a material for making vessels, scrapers, and knives lies in the fact that copper can be shaped by hammering, drawing, or casting, whereas flint can be shaped only by chipping. Yet this information undoubtedly came to primitive man very slowly as a result of working with the metal. Similarly, some early observer noted that the seasons could be related to the height of the sun in the heavens at midday, and that the time that elapsed from new moon to new moon was about thirty days. Upon these observations, early man based a division of time into the month and the year. In this way all early cultures slowly accumulated.

The dawn of our present civilization began in early Egypt along the Nile

[1] Breasted, J. H., *Ancient Times*. Boston: Ginn and Company, 1935, page 66.

and in ancient Babylonia and Chaldea along the Tigris and Euphrates Rivers. Here, in regions of great fertility and mild climates, two civilizations, based largely upon an agricultural economy, arose almost simultaneously. Intellectual advances in these early civilizations were largely the result of empiricism and accident. Often these advances resulted from the necessity of overcoming some difficulty in connection with the business of making a living. For example, the planting of crops is dependent upon the seasons. It became a very practical problem, therefore, to know when to plant the wheat crop. The calendar, with a year of three hundred and sixty-five days based upon the apparent movements of the sun, was perfected in Egypt as early as 4241 B.C.

The fruitfulness of the empirical method of extending knowledge was far from inconsiderable. The ancient arts of tanning leather and of making glass, the use of natural dyes, the making of boats, the spinning of high-quality textiles from wool and camel's hair, are examples of skills of high order. Even before 2000 B.C., the practical arts were highly developed by the people living in the valleys of the Nile, Tigris, and Euphrates. They traveled in large ships and in vehicles; they had beds and chairs, exquisite jewelry, combs, rouge, hats, shoes, and razors. The Egyptians used $3\frac{1}{7}$ as the value of π. A more precise value of this constant was not known until the time of Archimedes (287–212 B.C.). These early peoples also devised units for coinage, for mass, length, and capacity. They worked out the elements of arithmetic and made the beginnings of geometry.

Fundamentally, the character of the culture of any nation is an indication of the extent to which its people have been able to make nature contribute to their physical well-being. Primitive man had practically no control over his environment, though he early attempted some control. Historically, man has tried to control his environment and to enrich his culture by three different methods: the practice of primitive religion, of magic, and finally of science.

Origin of Primitive Religion

Primitive man always ascribed phenomena that he did not understand to the operation of supernatural forces. This quite naturally led to a personification of the forces. Primitive religions are all characterized by a great multiplicity of gods. There was a god to control the growth of the crops, others to control hunting, fishing, the rains, and the like. The entire period needed for the planting, growing, and harvesting of crops, for example, was broken with many religious holidays to do honor to the god of the crops so that he would be moved to reward his followers with bountiful harvests. Crop failures or famines were accepted as punishment for acts displeasing to the gods. It is easy to see why people dominated by religions of this type could not do very much to accelerate the rate of growth of new knowledge.

The Function of Magic

Man's first attempt to control his environment for his own betterment was through the use of magic, a practice still widely followed. There are even yet many agriculturalists who insist that the proper time to plant potatoes is during the first dark of the moon after Good Friday. All primitive peoples have had the idea that desired events could be brought about by carefully going through certain ritualistic rites. Magic was a way of looking at the world which resulted in the elimination of fear of an environment which was not understood. It is difficult for us to conceive of people who never carried on any activity, such as building a home, starting on a journey, treating an illness, or cooking a meal, without first going through a ritualistic ceremony in the belief that, if the ceremony was correct, success was insured. Among people who practiced magic, the most honored persons were the magi or wise men who knew the particular ritual needed to achieve a particular result. We are far removed from primitive man, but nevertheless the practice of magic is still popular. Perhaps you know someone who carries a rabbit's foot or hangs a horseshoe over a door to bring "good luck." And we still launch modern battleships with a ceremony which includes breaking a bottle of wine over the prow to start them off on a successful career. Many a banquet is marked by drinking a toast to an honored guest. These are but modern relics of the ancient practice of magic.

Origin of Science

Both religion and magic were important parts of all early cultures. Science was relatively unimportant or unknown. It appeared much later, but it has become increasingly important until now it is the most important single force in modern culture. Science is a method of thinking and an attitude toward life and environment that more than any other single factor is responsible for the changes that have occurred in our manner of living during the past century. The significance of science can be pointed out by calling attention to the increase in the average life-span of humans. It is said that the average span of human life during the Middle Ages was twenty-one years; by 1780 this had increased to twenty-six years; by 1825 it was thirty years; by 1850, forty years. The figure has continued to increase with the progress of science. The figures of the United States Census Bureau for the last forty years are especially striking:

1900	50 years
1920	57 years
1930	59.2 years
1940	62.5 years

This increase in the average span of life is due to scientists working prin-

cipally in the fields of chemistry, physics, medicine, sanitation, agriculture, and engineering. Workers in these varied fields have evolved the modern methods of sanitation, the knowledge and methods of control of diseases, the present understanding of adequate diets, and the better and more abundant food supplies, which have prolonged the expectation of life for all.

The beginnings of science are obscure. It is safe to say that science began when individuals became curious about events and began to collect, study, and record facts concerning them. Slowly the conviction arose that nature is intelligible. If nature is knowable, then it would often be possible to make predictions of certain natural events and thus attain a measure of control over nature. To many primitive peoples, an eclipse of the sun was an awesome event. But Babylonian astronomers made a record of eclipses they observed. In time this record enabled them to predict eclipses because they found that they did not occur erratically, but at regular intervals of eighteen years and ten or eleven days. The division of the year into twelve months, the seven-day week, the division of the day into twenty-four hours, the hour into sixty minutes, and the minute into sixty seconds, we also owe to these early Babylonian astronomers.

Science made but very slow progress until the rise of Grecian culture, when Greek thinkers demonstrated the power of scientific thinking. The credit for first extensively employing the scientific method belongs to the Greeks. A combination of circumstances made Greece the home of a civilization dominant for a thousand years. The cultures which developed around the eastern Mediterranean gradually moved northward and westward. By 1200 B.C. highly developed cultures were established on many of the islands, and on the mainland around the Aegean Sea. Historians refer to these cultures as the Cretan, the Minoan, and the Mycenaean. Into these civilizations migrated vigorous barbarians from the north, and from this mixture of stock Greek civilization gradually developed. It began to flower about 600 B.C.

Greek civilization differed in many ways from the civilizations that had developed in the valleys of the Nile and of the Tigris-Euphrates Rivers. These were composed of great masses of homogeneous peoples held together by strong centralized governments. The mountainous character of Greece resulted in the development of many small independent city-states. These small city-states never became burdened with institutionalized religion and a priestly class interested in the *status quo*. The Greeks gained distinction by participating in the duties of a government of thinking citizens. The mark of intelligence came to be curiosity in all activities of human life, and thus the Greeks became interested in knowledge, not because of its utilitarian value, but for its own sake and for the personal satisfaction attained in seeking knowledge; they were interested in all questions and in all phenomena. The inclination to inquire, to discuss, to argue, to discover

relations, became a passion. They set up criteria for testing the validity of reasoning. In short, the important contribution of the Greeks was their conviction that the universe was one of law and order, understandable by man. Without this fundamental concept, there could be no science. During the period of about five hundred years (600–100 B.C.), the Greeks made more striking advances in the field of the natural sciences than had been made in all of previous recorded history, and set a record that was not to be equaled until the seventeenth century of our era.

The contributions of Greek scientists make an imposing list. Thales (*ca.* 580 B.C.) visited Egypt and was impressed by the empirical rules used for land surveying. From these rules Thales derived certain axioms and postulates which became the basis for geometry. From these relatively few axioms and postulates it was possible to deduce an immense number of consequences by *logical reasoning processes alone.* Pythagoras (*ca.* 550 B.C.) extended the work of Thales in geometry. He gave the first proof that the square of the hypotenuse of a right triangle is equal to the sum of the squares of the other two sides. The Greeks tackled the problem of the constitution of matter. Later in this volume, we shall study Dalton's atomic theory in connection with chemistry, and shall find that the concept of atomism — that all matter is composed of small particles called atoms — goes back to Democritus (*ca.* 420 B.C.). This concept has had tremendous influence on the thinking of man.

The greatest of the ancient scientists from the standpoint of his influence on human thought was Aristotle (384–322 B.C.). His ideas were destined to influence the pursuit of all knowledge down to the present time. Aristotle was an exceedingly lucky and talented individual. He was the son of the court physician of King Philip of Macedon. His unusually keen mind was thoroughly schooled under the famous Greek philosopher Plato. He was associated with Alexander the Great, first as tutor, and then as a recipient of financial support for his school of science.

Aristotle made many lasting contributions to human thought and science. One of his most important contributions was to point out clearly the meaning of the *inductive method* of advancing knowledge. This method requires first facts, and then more facts as a basis for the extension of knowledge. He pointed out the dangers of trying to advance knowledge by reasoning processes divorced from the world of sensory experiences. At the same time Aristotle emphasized that science results only from the proper utilization of factual material. He therefore formulated the principles of sound reasoning and thus was the creator of formal logic.

In creating certain fields of study, such as zoology, embryology, and physiology, Aristotle was unusually successful. In other fields, as astronomy and physics, his efforts came to naught. In these fields, he failed because he did not always follow his own *modus operandi:*

> We must not accept a general principle from logic only, but we must prove

its applicability to each fact; for it is in facts that we must seek general principles, and these must always accord with facts, from which induction is the pathway to general laws.

In fairness to Aristotle, however, it must be stated that some of his erroneous generalizations were due to the inability at that time to get the facts to check his own conclusions.

The reputation of Aristotle, great even in his own day, increased with time. During the revival of learning in Europe following the Dark Ages, the science of Aristotle and his laws of logic came to represent the absolute truth. Aristotle was considered right in all matters. It is ironical that Galileo and Copernicus and other workers who were partly responsible for the second great appearance of the scientific spirit were frequently persecuted by those in authority who insisted on the absolute truth of some of the wrong conclusions of the long dead Aristotle.

No story of Greek science is complete without mentioning Archimedes (287–212 B.C.). Archimedes was a modern, seventeen hundred years ahead of his time. He was unusually successful in applying the principles of science to the solution of practical everyday problems. Furthermore, he expressed important ideas in the concise language of mathematics. He proved that the value of π was greater than $3\frac{10}{71}$ and less than $3\frac{10}{70}$. He discovered the laws concerning pulleys, the lever, and hydraulic screws, and stated the law of floating bodies. To him we owe the concept of density. His method of attacking a problem was truly scientific. He isolated a relatively small problem, studied it experimentally, drew his conclusions, and then checked them by experiment. This greatest scientist of the modern type in the ancient world was killed by a Roman soldier after the conquest of Syracuse in southern Italy in 212 B.C. The frontispiece illustration shows Archimedes at the moment the Roman soldiers broke into his study.

Science in Alexandria. Greek influence in the advance of knowledge was at its height from 700 to 200 B.C., though not always in Greece itself. Alexandria in Egypt became the intellectual center of western civilization about 300 B.C. and continued dominant until about A.D. 400, even during the period when the center of government was in Rome. The Roman genius lay in the field of law and in solving the practical problems of government. The Romans built excellent roads, aqueducts, and public buildings, but contributed little to the advancement of science. From the center of Grecian learning in Alexandria, however, notable contributions to knowledge continued to come. Hipparchus (*ca.* 140 B.C.) discovered the precession of the equinoxes, and calculated the distance to the moon and the moon's diameter with an accuracy that is surprisingly close to the values we accept today. Euclid wrote his geometry in Alexandria. Eratosthenes (*ca.* 225 B.C.), while librarian of the great museum in Alexandria, satisfied himself that the earth was essentially spherical and even deter-

mined its circumference. His value differed from the present accepted value by less than half of one per cent, a truly remarkable achievement.

The outstanding Alexandrian scientist, in his influence on human thinking, was the astronomer Claudius Ptolemy (A.D. 127–151). His great work, the *Almagest*, is really an encyclopedia of astronomy. It was in this work that he expounded the geocentric conception of the universe. This is the conception that the earth is the center of the universe, and that the moon, Mercury, Venus, and the rest of the planets travel in circular orbits around it. This conception had been taught by Aristotle, although he had never considered the problem of the motions of the planets with the attention to detail shown by Ptolemy. It is for this reason that the geocentric conception of the universe came to be referred to as the *Ptolemaic system.*

We have written of the achievements of the Greek scientists. But they had certain weaknesses that should be pointed out. The Greek scientists often failed because they were content to rely too much on intuition or reasoning processes alone. They seldom stopped to verify their theories and conclusions experimentally. This was in part because the Greek citizen placed experimental work on a par with manual labor, which was reserved for slaves. But in spite of its defects, the Grecian period represents the first flowering of the methods of science. An exceedingly large number of fundamental ideas which form an important part of our culture, we owe to the Greeks.

The Decline of Learning. The thousand-year period following A.D. 400 was almost entirely devoid of scientific advances. It is the early part of this period which is often referred to as the Dark Ages. Civilization was virtually eclipsed by the hordes of barbarians from the north moving into the decayed societies to the south. The learning of the Greeks would have disappeared but for the guardianship of knowledge by the Arabs, the Mohammedans, and by the scholars of the eastern Roman Empire centering in Byzantium. The empire of the Arabs flanked the Mediterranean as far west as Gibraltar and Spain. The only significant advances, largely in the fields of mathematics, optics, and chemistry, were made by the Arabs. The major intellectual force during this long period was the Church. The learning of the Greeks all but disappeared. Fortunately, however, manuscripts of the contributions of the Greek philosophers and scientists were preserved in monasteries. About A.D. 1200, the philosophy and teachings of Aristotle came to be accepted by the thinkers of the Church and were reconciled with the teachings of the Church fathers. The leading exponent of this fusion was Thomas Aquinas (*ca.* A.D. 1260), whose greatest work was the *Summa Theologica.* This fusion movement is referred to as *scholasticism.* Most of the great university centers of Europe — Paris, Florence, Padua, Pisa, and the like — were fostered by the Church and in all of them the ideas of Aristotle exerted a tremendous influence. As has been explained before, the notions of Aristotle in the physical sciences

were often quite erroneous, but nevertheless his prestige was so great that for a period of more than a thousand years his mistaken conceptions actually hindered advances in science.

Modern Science

The second flowering of the scientific method is associated with the names of Copernicus, Kepler, Galileo, and Newton at the time of the Renaissance. This movement, a complex social, religious, economic, and scientific reorganization of the nations in western Europe, resulted from a broader mental outlook as a result of the diffusion of learning by the extensive use of the new art of printing and the stimulus to industry and commerce resulting from the exploitation of the wealth of the New World and the Indies following the voyages of discovery by Christopher Columbus, Magellan, and many others. There were many material, moral, and intellectual factors which developed simultaneously to result in the great unfolding of the human spirit which is called the Renaissance. The development of science during this period was a very important part of the whole movement.

The state of science at the beginning of the sixteenth century is indicated by the fact that the motions of the heavenly bodies were still interpreted by the Ptolemaic or geocentric conception of the heavens — the earth was the center and controlling force in the universe. Copernicus (1473–1543)

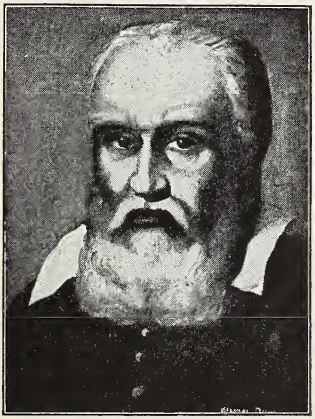


FIGURE 2. GALILEO GALILEI
1564–1642
(*Courtesy of* Science Service)

FIGURE 3. JOHN KEPLER
1571–1630
(*Courtesy of "Scripta Mathematica"*)

advanced the heliocentric or sun-centered conception of the solar system. But the forces, social, religious, and governmental, of his day were so opposed to science that Copernicus did not dare publish his ideas until he knew he was about to die. John Kepler (1571–1630) went on to express the motions of the planets in precise and comprehensive laws which established our present conception of the universe. But the first great protagonist of modern science was Galileo (1564–1642). He was a giant intellectually, a man of the world, an engaging and effective teacher, a resourceful experimenter, a practical mathematician, endowed with a crusading spirit for the cause of science. Galileo's insistence on the immutability of facts often resulted in serious difficulties with the authorities of his day. His ability to heap scorn and ridicule upon those who could not forsake the ideas of Aristotle and Ptolemy helped to establish the methods of science, but meant for him a stormy career. Galileo's fame spread through Europe and has not diminished with time. It can truly be said that Galileo started science on the path down which it has moved to the present time.

It is impossible to discuss modern science without frequent reference to *Sir Isaac Newton*, who possessed one of the best minds of all time. Newton was born the year Galileo died (1642), and from early manhood until his death in 1727 was continuously in the service of society as an investigator and teacher in England's great University of Cambridge, and as Master of the Mint in London. His contributions to thought were enormous: he founded mechanics — the basis for all the physical sciences, originated the science of optics, and extended enormously the techniques of mathematics. But most important of all, he popularized the methodology and philosophy of modern science, based on the premise that all nature is governed by orderly laws which are understandable by man.

In the realm of philosophy one often reads of Newtonian science. This reached its apex of development during the nineteenth century. Then just at the dawn of the present century there occurred the discovery of X-rays and radium. These discoveries, little understood at the time, initiated the train of events which was to culminate in the atomic bomb of 1945. This event was a triumph of the post-Newtonian physical science, the science of relativity and quanta, of Einstein, the Curies, Rutherford, Compton, Lawrence, Bohr, and many others whose discoveries led directly or indirectly to the development of nuclear energy. The contributions of each of these scientists will be presented later in this volume.

The broad sweep of science has very briefly been described here. Much of the work of this volume will be concerned with unfolding the story of the physical sciences. Reference will be made many times to the scientists mentioned in this chapter, in connection with their contributions to the history of science and their part in developing the outlook that we

have toward nature today and the method of thought that we call scientific. A preliminary discussion of the nature of scientific thinking is a subject for the next chapter.

SUMMARY

1. The early cultures of man advanced very slowly for three reasons: (*a*) the lack of a system of writing; (*b*) the empirical method of obtaining new knowledge; and (*c*) the lack of a scientific attitude toward nature.

2. Historically, man's effort to control his environment to advance his personal well-being has been along three different lines: (*a*) the practice of primitive religion; (*b*) the practice of magic; and (*c*) the use of science.

3. Early man personified as gods the many forces in nature which he did not understand. Primitive religion had for its object the control of nature for the benefit of man, through ceremonies pleasing to the gods.

4. The early widespread practice of magic was based on the conviction that desirable events are the result of the proper practice of certain ritualistic exercises.

5. The first important advance of science which resulted in significant changes in culture occurred in Greece and in Alexandria, Egypt, during the years 500 B.C. to A.D. 200. Some of the outstanding scientists of this period were Thales, Euclid, Pythagoras, Aristotle, Archimedes, Hipparchus, Eratosthenes, and Ptolemy.

6. Some important contributions of Grecian science were: (*a*) the discrediting of magic and superstition by emphasizing that it is possible to understand nature; (*b*) the glorification of reason; (*c*) the formulation of laws of logic; (*d*) the necessity of tolerance; (*e*) the development of certain important branches of mathematics, especially geometry and trigonometry; and (*f*) an attitude of mind that resulted in an effort to understand all phenomena in nature.

7. The principal shortcomings of Grecian science were: (*a*) too great dependence upon intuition and reasoning divorced from experiment; (*b*) too little desire to experiment; (*c*) an inability to apply science to life situations, business, affairs of government, and the like; and (*d*) too great a fondness for mere rhetoric.

8. The second flourishing of science occurred during the Renaissance in Europe, and is largely associated with the work of Copernicus, Kepler, Galileo, and Newton.

9. The present period of rapid growth of science — the third — began in the twentieth century. This period is associated with such recent scientists as Einstein, Pierre and Madame Curie, Rutherford, and Bohr.

STUDY EXERCISES

1. Neolithic stone man fashioned many tools and weapons of flint, which was relatively easy to chip into shape and which took a high polish. These tools and weapons were a vast improvement over the crude granite tools and weapons of Paleolithic stone man. Did this transition occur slowly — during many generations — or rapidly? Was it largely the result of a process of trial and error or the result of experimentation? Discuss.
2. Many familiar utensils, tools, jewelry, and the like, are now being made of various plastics instead of the wood or metals formerly used. These plastics were hardly known thirty years ago. Was this largely the result of a process of trial and error or the result of deliberate experimentation? Discuss.
3. When Cortez (A.D. 1520) with a relatively small army, equipped with firearms and artillery, conquered the Aztec nation in Mexico, he found a civilized nation. The Aztecs, however, knew nothing about the wheel and its applications. List as many devices as you can that the Aztecs did not possess because of their lack of knowledge of the wheel. By what process may the concept of the wheel have come into our culture?
4. All the individuals listed below made significant contributions to the advancement of human thought. Give the time in which they lived, their country, and their important contributions.

Name	Dates	Country	Important contributions
Euclid			
Pythagoras			
Aristotle			
Archimedes			
Ptolemy			
Copernicus			
Kepler			
Galileo			
Newton			

5. List as many differences as you can which show how the modern scene — your environment — differs from that familiar to your grandparents. How do you account for the differences?
6. Stone Age man could transmit accumulated knowledge from one generation to another for the most part only by word of mouth or example. List the methods that are now available for the preservation and transmission of knowledge. How many of these methods are relatively recent applications of scientific principles?
7. There are a number of reasons that motivate men to perform the work necessary to make new discoveries, such as (*a*) the desire to satisfy individual curiosity; (*b*) the desire for monetary returns; (*c*) the desire to help their fellow men; (*d*) the wish to receive the acclaim of their fellow men, and so on. Which of these motives have predominated in the lives of those individuals who have made unusual contributions to the total sum of human knowledge?

8. What can be said of the relative number of significant discoveries made by the use of the empirical method and by the scientific methods of thinking at the present time?

FOR FURTHER READING[1]

1. Taylor, F. S., *The March of Mind.* New York: The Macmillan Company, 1939.
Chapters I, II, and III discuss the beginnings of science, the rôle of primitive religion, magic, and science in early cultures, and the science of Greece.

2. Sedgwick, W. T., and H. W. Tyler, *Short History of Science.* Revised edition. New York: The Macmillan Company, 1939.
A discussion of the relation of the applications of scientific thinking — applied science and invention — to social and economic progress will be found on pages 328–448.

3. Barnes, H. E., and Henry David, *The History of Western Civilization.* New York: Harcourt, Brace and Company, 1935.
An excellent account of primitive stone, bronze, and iron cultures is found in Chapter I. Chapters VI and VII discuss the rise and fall of Greek civilization. A concise evaluation of Greek science is given on pages 218–231.

4. Loeb, L. B., and A. S. Adams, *The Development of Physical Thought.* New York: John Wiley and Sons, 1933.
The rôle of magic and primitive religion in early cultures, the origin of science, and the broad outlines of its progress in western cultures up to the time of Newton are discussed in Chapter I.

5. Harsányi, Zsolt, *The Star Gazer.* New York: G. P. Putnam's Sons, 1939.
The life of Galileo in novel form. Entertaining and instructive reading.

[1] It is very desirable for a student in the broad area of the physical sciences to read some of its original literature. But the vastness of this literature and its dispersal throughout a number of different scientific disciplines make this very difficult for the general student. For this reason the authors recommend for collateral use with the present text such a volume as *Readings in the Physical Sciences*, edited by Harlow Shapley, Helen Wright, and Samuel Rapport (New York: Appleton-Century-Crofts, Inc., 1948). The editors present a very carefully selected series of readings covering science and the scientific method, astronomy, geology, physics, and chemistry. These readings by outstanding scientists will supplement the material presented throughout this text and enrich and broaden the understanding of the new student in the field of the physical sciences.

2

The Tools of Inquiry

MANKIND CAN ADVANCE only by converting more of the unknown into the known. Newton, in the twilight of his life, wrote: "I seem to have been only like a boy playing on the seashore, and diverting myself in now and then finding a smoother pebble or a prettier shell than ordinary, while the great ocean of truth lay all undiscovered before me." Newton, by an almost fanatical adherence to the principles of the scientific method of thinking, laid the foundation for our present-day conception of the universe and made the modern physical sciences possible. LaGrange, an eminent French mathematician, paid this tribute to Newton: "Newton was the greatest genius that ever existed and the most fortunate, for we cannot find more than once a system of the world to establish."

What, then, is this scientific method which has led to so many discoveries? It consists in the intimate union of experiment with reason; it is both deductive and inductive in its processes. It differs from the empirical method in that the experiments are not made at random, but are guided by reason. Furthermore, the reasoning processes are always linked to objective facts by experiment. Scientific thinking is not a stilted process that must follow certain prescribed steps. It is at times extremely complex, but usually it follows a certain general pattern of procedure.

STEPS IN SCIENTIFIC THINKING

In order to think scientifically, it is first necessary to form a definite opinion of a problem. Thus, Edison set out on the path which led to the perfection of the incandescent electric light bulb when he had a clear picture in his own mind of the possibility of securing light by the passage of an electric current through a filament of wire. He foresaw also the difficulties he would have to overcome. Some of the problems that Edison had to solve concerned the nature of the filament, the type of container to be used, a method to keep the filament permanent when operated for long periods of time at a high temperature. Often in many situations, a problem may be so involved and complex that the only hope of solution is to delimit

t. The successful solution of the smaller parts of the problem permits a gradual solution of the whole.

After recognizing the nature of a difficulty or problem, the second step s to assemble all possible objective facts pertaining to it. This must be lone without bias or preconceived notions which may unconsciously cause he accumulation of certain facts and the disregarding or overlooking of ther facts. It is impossible to overemphasize this aspect of scientific hinking. Every fact must be accepted as it stands irrespective of any lesire to make it fit into a pattern of thinking. It is dangerous to ration- lize too soon while collecting the facts necessary to solve a problem. This vas one of the reasons for the failures of many of the followers of Aristotle. They worshiped human reason and authority, and thus were not able to ee, or willfully disregarded, certain troublesome facts. The true scientist nust accept all objective facts even though he does not understand their ignificance. It is a common experience with scientists that in connection vith some problems there is such a paucity of fact-material that it is neces- ary to devise and conduct experiments for the deliberate object of acquir- ng a body of fact-material to use in solving the original problem. Here it s necessary to bring out clearly the meaning of the term *objective evidence.* When facts concerning a given problem can be accumulated by different ndependent experimenters and described similarly in terms of some scheme f measurement, they can be said to be *objective.* Facts described in terms f individual opinion without resort to quantitative measurement in tandardized units are *subjective,* and must be studiously avoided in scien- ific thinking.

Scientific Laws

The third step in scientific thinking usually results in some kind of classi- ication and systematization of the facts. This procedure often ends in a generalization which is referred to as a *scientific law.* A scientific law is nerely a concise statement of some uniform mode of behavior that has been hown to be true from the study of an array of facts pertaining to a certain henomenon. We are actually familiar with many of these laws, though ve often do not think of them as laws. For example, the ratio of the cir- umference to the diameter of any circle is a constant number, 3.1416.... This is a generalization deduced from a study of the facts pertaining to many circles, and no one has yet discovered a circle for which this ratio de- parts from the value given above. This simple example, incidentally, il- lustrates the economy of effort, mental and physical, that results from a knowledge of scientific laws. Imagine, now, that we did not have this law f the circle. A tinsmith is to make a round tank with a certain diameter. He will need to know the length of the circumference. Without the law of he circle, he would have to trace out a circle on the given diameter and hen actually measure the circumference with a measuring tape. This

would be a time-consuming operation, and the result could not possibly be as accurate as the simple procedure of finding the product of the diameter multiplied by 3.1416.

Scientific laws differ from man-made laws in that they refer to phenomena in nature beyond the control of man. Any legislative body can, for example, change the speed limit on a public highway, but for that same legislature to attempt to change the numerical value of π would be a nonsensical procedure.

Induction. The phase of logic involved in finding general laws from a study of assembled facts is called *inductive reasoning*, and is of special importance in experimental science. It is characteristic of the physical sciences that these generalizations are often expressed in the precise symbols of mathematics. Thus, the generalization concerning the circle given above can be expressed,

$$\frac{\text{C(ircumference)}}{\text{D(iameter)}} = \pi = 3.1416\ldots$$

It is especially important that inductions from a mass of facts be demonstrably true by experiment. Hence, generalizations cannot be accepted until verified by ample observation and experiment. They will be accepted as true only so long as no new facts are discovered which cause the law to be questioned.

Deduction. Scientific laws are important because they result in an economy of time and effort for all who apply them. A science is well along the path toward usefulness when a large number of laws have been formulated. Many of the practical problems of life can be solved by the mere application of these laws. This is the phase of logic called *deduction* — the application of a general law or principle to a new situation. Thus, someone may raise the question of the relationship between the hypotenuse and the two legs of a right triangle. The answer can be found in more than one way, by making use of certain broad generalizations which are a fundamental part of geometry.[1] Deduction is the reasoning process employed when we proceed from previously systematized and accepted knowledge. There can be only one criterion as to the correctness of any conclusion reached by deduction — experimental verification. As has been stated before, many of the conclusions of the Greek scientists and philosophers were erroneous. Their conclusions were reached by reasoning alone with no final verification by controlled, deliberate experimentation. In short, to be scientific thinking must begin and end in experiment.

Working Hypotheses

The work of a true scientist does not stop with the induction and application of general laws. He is not only interested in a concise statement o

[1] The final conclusion is the famous theorem of Pythagoras already mentioned.

ow things behave, but he is even more interested in *why* they behave as hey do. This leads to the fourth step, one of the most important in scien- fic thinking — the formulation and testing of *working hypotheses*. An ypothesis is merely a working "guess" as to why certain *causes* invariably ad to certain *effects*. An hypothesis is of little use unless it can do what it designed to do, i.e., *explain* clearly and completely. Hence, an hypothe- s must always be tested *experimentally* or *observationally*. This testing rocedure links the hypothesis to reality; it may confirm it or it may con- adict it. If it contradicts, it must be discarded in favor of another ten- ative explanation, to be similarly tested. It often happens that a part of he hypothesis must be modified while the rest remains unchanged. The ew or modified hypothesis must again be subjected to the test of experi- ent. This interplay of experiment with reason is the essence of the scien- fic method.

cientific Theories

Only when an hypothesis has stood the test of many experiments de- gned to check it, does it attain the rank of a *theory*. The theories of science rm the framework upon which the facts hang. They tie apparently un- lated observations together and enable us to see the connections between em. This is one of the important functions of any theory. Later, we all see that many phenomena concerning the universe are organized round the theory and law of gravitation, that of chemistry around Dal- on's atomic theory, that of heat around the kinetic molecular hypothesis.

The most important function of a theory is to lead the way to further dvances of knowledge by suggesting new experiments or fields for re- arch. The average layman often does not realize that most significant iscoveries now being made are the result of the application of theories hich, strangely enough, may not be permanent in themselves. The edi- rial writer of the daily newspaper is often inclined to heap scorn on theory nd theorists, but this is from a lack of appreciation of the true signifi- nce of a scientific theory. One of the greatest medical advances of the st two decades was the discovery of insulin. Insulin is the hormone sup- ied to the blood by the pancreas, the lack of which causes diabetes. Vithout a working hypothesis, it would never have been discovered. Sim- arly, a working hypothesis was all that Edison had to guide him when he as doing the experimental work which led to the perfection of the electric ght bulb. We are to learn later that it was the electromagnetic theory of diation devised by Clerk Maxwell, the English scientist, that pointed out e possibility of the existence of radio waves, which later were experimen- lly proved to exist by the German scientist Hertz, and which Marconi ill later used for wireless communication. Among the outstanding de- elopments of modern chemistry are synthetic rubber and synthetic tex- le fibers superior to natural rubber and fibers. They are possible because

of the application of a theory concerning the behavior of what the chemis calls *unsaturated molecules* and their linkage together by a process calle *polymerization.*

Theories usually are in a state of flux and improvement. Occasionall new facts are discovered which cast doubt upon the validity of an accepte theory. In case a theory does not harmonize with new facts, however in significant, it is the theory that is modified or even discarded. Facts ar always the final standard for judging the truth of a theory. The reaso that this is not more generally realized is that one never hears of the work ing hypotheses that were invented, tested against the known facts, and dis carded because they were found wanting. The only theories we usuall hear about are the successful ones.

Let us consider a not uncommon difficulty about which you can proce scientifically or unscientifically. Suppose you are reading some evenin and your table lamp suddenly goes out. You immediately have a practica problem on your hands. From past experience in situations like this yo quickly devise four working hypotheses, which you think should enabl you to overcome the difficulty: (1) the power has been turned off at th power station; (2) there has been a break in the power line between th power station and your home; (3) a fuse in the fuse box in the basement ha been "blown"; (4) there has been a failure of the filament in the light bul Note that these hypotheses are based upon many facts that you have a your command, and that these facts have been systematized and genera ized. You next experimentally test each working hypothesis in tur The first hypothesis is quickly eliminated because if the power had bee turned off at the power house, all the lights in the neighboring homes woul also be out. Instead, they are still lighted. The second hypothesis is als quickly eliminated by merely turning on the lights in the next roo Since they immediately light when you try a switch, the power line into th house is still functioning. This same test likewise eliminates the thir hypothesis, proving that there has been no failure in a fuse for you reca that the circuits in these two rooms use the same fuse. There is still th fourth hypothesis to check. You screw out the light bulb that failed an try it in a lamp socket in the next room. Lo, it lights! and the fourt hypothesis has been proved false. Momentarily you are baffled. Wha can be done? Forced to invent a new working hypothesis, you realiz that there may have been a failure in the lamp circuit itself. You the follow the lamp cord to the outlet in the wall, and sure enough, the attac ment plug had loosened enough so that there was no electrical contac The problem has been solved by going from experiment to hypothesis an back to experiment again.

Reference has already been made to the discovery of insulin. In pri ciple, the steps leading to the discovery of insulin differ little in procedu from our problem of the failure of the table lamp except that the proble

was much more complex, and required the acquisition of a much larger body of fact-material pertaining to the disease of diabetes and the invention and testing of many more working hypotheses, until finally an hypothesis was invented which was successful in leading to the discovery of insulin.

The symbols and language of mathematics are very prominent in scientific thinking. There needs to be an emphasis from the beginning that science without mathematics is impossible just as our modern social and economic life would be impossible without mathematics.

> The man of the machine age is a calculating animal. We live in a welter of figures: cookery recipes, railway time-tables, unemployment aggregates, fines, taxes, war debts, overtime schedules, speed limits, bowling averages, betting odds, billiard scores, calories, babies' weights, clinical temperatures, rainfall, hours of sunshine, motoring records, power indices, gas-meter readings, bank rates, freight rates, death rates, discount, interest, lotteries, wave lengths, and tire pressures.[1]

In science just as in life the process of making comparisons cannot be avoided. Quantitative measurements so-called are of the essence of science. But that should not be a matter of concern for the person unfamiliar with many of the special techniques of the mathematician. The only mathematics needed for the introductory material in this volume is the mathematics of ordinary living.

Mathematics is a Language

Historically, mathematics has always been intimately associated with practical, everyday affairs. The use of numbers came into being as a result of problems that arose out of making a living and making a life. Mathematics is very definitely a language perfected in response to certain social and scientific needs. An inability to understand this language means an inability to understand our modern economic and industrial age and many phenomena of nature that concern us all. If we are to understand the manner in which Newton derived the law of universal gravitation or the mechanics of this machine age, we cannot avoid learning to speak, read, and write in a *quantity language*, a *size language*, a *position language*, and a *time language*. In this chapter we shall discuss the first three. As early as 1100 B.C., Phoenician navigators sailed through the Pillars of Hercules, out into the Atlantic, and north to the tin mines in Cornwall, England. They successfully solved the problem of the *length* of this voyage. The maps used by these ancient navigators to depict the then known world were surprisingly accurate, even when judged by modern standards. See, for example, Figure 4.

The Phoenician navigators were also traders. They early learned that to sell their wares in terms of volume was often very difficult or impossible. The purchaser of a load of tin from England, for example, was concerned

[1] Lancelot Hogben, *Mathematics for the Million*. Revised edition. New York: W. W. Norton Company, 1943.

FIGURE 4. MAP OF THE WORLD BY HECATAEUS, 517 B.C.
(*From Breasted's* Ancient Times)

with the question of the amount of matter in his shipment — a problem of weight or mass. In life situations we must continually talk in terms of a size language dealing with lengths, areas, volumes, and weights. We carry out these measurements by comparisons with certain standards which constitute a system of weights and measures. Our modern system of weights and measures differs only in ease and precision of application, not in principle, from the one used by the ancient Babylonians. The Babylonian units of length were the *finger*, about two-thirds of an inch, the *cubit* or thirty fingers, the surveyor's *cord* or 120 cubits, and the *league* which was 180 cords (or about 6.65 miles). The *talent* was their unit of weight, about $67\frac{1}{2}$ pounds.

THE LANGUAGE OF QUANTITY

Before he became an agriculturist, primitive man was a herdsman. His wealth was reckoned by the number of sheep he possessed. There is objective evidence that early man used a great variety of methods to keep track of the amount of his wealth, such as tallying in pebbles, or with small sticks or making notches on a stick. Many clay tablets found on the site of ancient Babylon show the gradual evolution of their number system. Thus the possessor of eleven sheep would record that fact in cuneiform charac

ers as follows, with a stylus in soft clay:

Eventually, the familiar grouping of ten seen in the fingers of both hands ed to a simplification: Here the horizontal impression was the ymbol for the quantity ten. The number sixty was very prominent in the Babylonian number system, and was indicated by a wedge-shaped impression similar to that for one except that it was considerably larger. Large umbers were represented then by some simple combination of three uneiform characters. Thus, the number eighty-one was considered as ne *sixty*, plus two *tens*, plus *unity*, and was represented:

The logic of the Babylonian number system is shown in Figure 5.

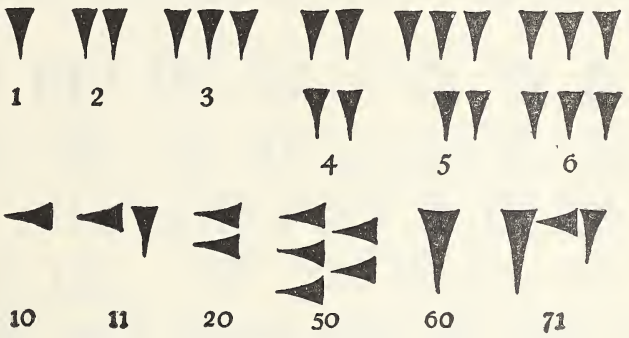


FIGURE 5

The Egyptians devised a number system based upon the number ten, hich was indicated by the symbol: Thus, the number 81 was onsidered as eight *tens*, plus *unity*, and was represented:

number system based upon the number ten is called a *denary* system. arious peoples have developed number systems on a base of twenty, a *gesimal* system, and on the base number twelve, a *duodecimal* system. Ve still have evidences of these former number systems, as in the expres-

sions, "threescore years and ten" as found in the King James version of the Bible, and in the phrase "fourscore and seven years ago," used by Lincoln in his Gettysburg Address. The division of the circle into three hundred and sixty degrees, the degree into sixty minutes, and the minute into sixty seconds, we owe to the sixty-base *sexagesimal* system of the Babylonians. The prominence of the number twelve, the dozen, the gross, the yard of thirty-six inches, the foot of twelve inches, the clock numerals, and many other examples that can be given show the convenience of the twelve-base duodecimal system, which came from the Romans.

The number system that prevailed longer than that of any other (not excluding our present one), was that of the Romans. The Roman system could systematically represent very large numbers, but it was difficult or impossible to use it for all mathematical operations of addition, subtraction, multiplication, and division. And it was for its convenience that the so-called *Arabic* system of numerals has superseded all former number systems.

I	II	III	IV	V	VI	VII	VIII	IX
1	2	3	4	5	6	7	8	9
X	XX	XL	L	LX	LXXX	XC	C	
10	20	40	50	60	80	90	100	
CC	CD	D	DC	DCCC	CM	M, *etc.*		
200	400	500	600	800	900	1000		

FIGURE 6

The Arabic system introduced two almost entirely new concepts, the zero and the principle of position. The zero indicates absence of number. The principle of position indicates various multiples of the base number, 10. These two devices make it possible to indicate concisely any number by employing the nine digits, 1, 2, 3, 4, 5, 6, 7, 8, 9, and the zero (0) with the base number 10. For example, what is the meaning of the number 3027 in the Arabic system?

$$\begin{aligned} 3027 = 3 \times 1000\ (10^3) &= 3000 \\ 0 \times\ 100\ (10^2) &= 000 \\ 2 \times\ 10\ (10^1) &= 20 \\ 7 \times\ 1\ (10^0) &= 7 \\ &\overline{3027}; \end{aligned}$$

$$3027 = 3(10^3) + 0\,(10^2) + 2(10^1) + 7\,(10^0)$$

The value assigned to any digit depends, then, upon its *position* in the number. Another example should make this clear. The number 50207 is a short notation for the operations indicated here:

$$\begin{aligned} 50207 &= 5\,(10^4) + 0\,(10^3) + 2\,(10^2) + 0\,(10^1) + 7\,(10^0) \\ &= 50000 + 0000 + 200 + 00 + 7 \end{aligned}$$

Without the concept of the zero, implying lack of number in a particular column or position, it would be impossible to represent large numbers conveniently.

The Arabic system is a denary system. The significance of this will be appreciated when it is understood that if used with another base number the present Arabic notation would represent entirely different quantities. In the duodecimal system, the notation 127 would represent 175 objects, since,

$$\begin{aligned} 127 &= (1 \times 12^2) + 2\,(12^1) + 7\,(12^0) \\ &= \quad 144 \quad + \quad 24 + 7 \\ &= 175 \text{ objects.} \end{aligned}$$

The Arabic system readily lends itself to the most difficult computations. This system actually originated among the Hindus, and the Arabs should be credited only with its introduction into Europe by way of Spain.

THE LANGUAGE OF SIZE

Units of Measurement

Reference has already been made to the fact that the physical sciences have been built upon a mass of objective quantitative fact-material. It is necessary, therefore, that the student have a working conception of the system of units now in scientific use. Every student has some familiarity with the English system of weights and measures. However, the basic system of weights and measures in this country and throughout the entire scientific world is the metric system. The English system lacks a rational basis, with the result that the relationships between the various units are difficult to remember and involve awkward arithmetical relationships. The metric system, on the other hand, is deliberately designed to be simple arithmetically and capable of indefinite expansion as it becomes necessary to invent new units.

The scientist recognizes two types of units, *fundamental* and *derived*. The fundamental units are three in number: the *meter* to measure lengths, the *gram* to measure masses (weights), and the *second* to measure time. From these three units nearly all other units can be derived. A unit of area such as the square meter, or a unit of volume such as the cubic meter, is a derived unit. Similarly, multiples or submultiples of the various fun-

FIGURE 7. THE NATIONAL STANDARD KILOGRAM IN THE VAULT OF THE NATIONAL BUREAU OF STANDARDS WITH BELL JARS REMOVED

The kilogram under the bell jars is a secondary standard. These were furnished by th International Bureau of Weights and Measures in 1875. *The standard kilogram wa taken back to Paris in* 1937 *for recomparison with the international standard. The mo careful tests showed that the United States standard had changed only one part in fift million in about fifty years.* (*Courtesy of National Bureau of Standards*)

damental units are derived units. The fundamental units for *length*, *mas* and *time*, respectively, are as follows:

The Meter. This is the distance between two marks on a platinum iridium bar kept at the Bureau of Standards in Washington, D.C., at th temperature of melting ice, 0° C. The bar[1] is a faithful copy of the origina which is kept at the International Bureau of Weights and Measures i Sèvres, near Paris, France. The meter is slightly longer than the yar being 39.37 inches.

The Gram. The standard kilogram is a reference mass of platinum iridium kept in Washington, D.C.[2] The original kilogram was intended t be the same as the mass of one thousand cubic centimeters of water at i maximum density, 4° C. However, owing to an unintentional error, th space occupied by this kilogram of water is actually 1000.028 cubic cent meters. This volume is arbitrarily referred to as the *liter*. From son points of view it can be considered the fundamental unit of capacity. Th milliliter is a common submultiple of the liter which is very nearly the sam as the cubic centimeter.

The Second. The second is one-sixtieth of one-sixtieth of one-twent fourth of one mean solar day. Another time unit is the *tropical year* the time required for the passage of the sun from vernal equinox to vern equinox, a topic which will be explained in Chapter 5. The discussion

[1] The primary standard in this country is The United States Prototype Meter No. 27.

[2] The primary standard of mass for both the metric and customary systems in this coun is The United States Prototype Kilogram No. 20.

he significance of these definitions will be postponed until the subject of time is considered.

The convenience of the metric system is the fact that the multiples and submultiples of the fundamental units are related by the factor ten or a multiple of ten. Thus, one-tenth of a meter is called a *decimeter;* one-hundredth of a meter is called a *centimeter;* and one-thousandth of a meter is called a *millimeter.* Similarly a unit a thousand times larger than the meter is called a *kilometer.*

Table 1. The Derived Units of Measurement

Submultiples	Fundamental Unit	Multiples
Decimeter: 0.100	Meter	Kilometer: 1000
Centimeter: 0.010		
Millimeter: 0.001		
Milligram: 0.001	Gram	Kilogram: 1000
Milliliter: 0.001	Liter	Kiloliter: 1000

The process of dividing the fundamental unit of length is sometimes carried even farther. Thus, the diameter of a red blood corpuscle is usually expressed in terms of the micron (μ), which is one-millionth of a meter. The millimicron ($m\mu$) is a thousand times smaller than the micron.

As has been mentioned before, units of area are derived units. A square one centimeter on a side is a square centimeter, designated cm^2. Similarly a cubic centimeter is abbreviated cm^3, a cubic meter, m^3, and so on. A common abbreviation for the cubic centimeter is cc.

Many students contend that the metric system is strange and difficult. It may seem a little strange, but it is not difficult. People continually use our coinage system, little realizing that it is a metric system in which the fundamental unit of value is the dollar, with the multiples and submultiples related by factors of ten. Consider Table 2:

Table 2. Metric Monetary Units

Submultiples	Fundamental Unit	Multiples
Decidollar: $0.100	Dollar	Kilodollar: $1000
Centidollar: 0.010		
Millidollar: 0.001		

The decidollar of course is the common *dime,* the centidollar is our *cent.* The millidollar is usually referred to as the *mill.* The average citizen has no trouble in handling our units of coinage; the units of the metric system are no more difficult.

We have had our metric system of coinage since 1792. When it was adopted, however, the force of tradition was so strong that the English system of measures was retained. However, by action of Congress, since 1893 the basic system of weights and measures has been the *metric system.* The legal definition of a yard, for example, is "a unit of length equal to 3600/3937 of a meter"; the pound is "a unit of mass equal to 0.453 592 427 kilogram."

It is unfortunate that our thinking must be in two systems of weights and measures. Only in the British Commonwealth and the United States do we find systems other than the metric in extensive use. In practically all the rest of the world, students are spared the task of becoming familiar with two systems of weights and measures. As long as this situation prevails in the United States, students will find it necessary to familiarize themselves with certain relationships between the two systems:

1 inch = 2.54 cm	1 kg = 2.2 lb
1 m = 39.37 in.	1 l = 1.057 liq qt
1 km = 0.62 mile	1 lb = 453.6 g

That the metric system is slowly gaining ascendancy in the commercial world is indicated by the fact that sizes of motion-picture films, weights on food labels, quantities in many physicians' prescriptions, tire sizes, calibers of guns, and so on, are now commonly expressed in metric units.

THE LANGUAGE OF POSITION

We are continually confronted with the elemental task of locating an object or an observer. Only one who has been lost in a great forest or at sea can truly appreciate the feeling of helplessness that comes over one in such a predicament, when he has absolutely no *frame of reference* by which to locate himself. A frame of reference is a pictural representation of some surface, often with suitable lines of reference known as *coordinates*. A familiar frame of reference is the neighborhood of one's own home. In many cities, the streets are laid out at right angles to each other to form a pattern of rectangular blocks. Often two streets at right angles to each other are designated as the reference streets, and then any place in the city can be located in relation to them. A map of the city, then, is a simple frame of reference with rectangular coordinates.

When we go on a trip by automobile, we transfer our frame of reference to a map which the gas station attendant donates to us. Throughout life we are confronted with the problem of our location. The same thing is true of any problem arising in the field of science, and the space language we use is the language of mathematics. Our understanding of the meaning of a square, circle, ellipse, parabola, or sphere takes on practical considerations. One of the momentous discoveries of the ancients was that we have no permanent frame of reference on the earth. The fortunes of war will change boundaries of countries; rivers change their courses; seas disappear; shore lines are augmented; mountain ranges slowly disintegrate or appear where none were found before. To get a permanent frame of reference, it is necessary to go to the heavens above us. This is one of the reasons why astronomy was among the first of the sciences to develop and why a language of space or geometry came into being. The scientist, like

wise, whether talking about the architecture of the universe or of an atom, nust resort to the language of space.

The grand assemblage of stars and constellations, whose positions with respect to each other remain fixed over long intervals of time, is known as the *celestial sphere*. It will be discussed later. Positions on the surface of the earth are located by giving their latitude and longitude. Latitude means angular distance north or south from an east-west reference line, the earth's equator. Longitude means angular distance east or west of the north-south reference line through Greenwich, England, which is called the *prime meridian*. Thus, in Figure 8 the city of Washington is uniquely located by giving its latitude and longitude. Its latitude, 39° N, is the distance in degrees along an arc of a circle perpendicular to the earth's equator, which also passes through the north pole of the earth. Its longitude, 77° W, is the distance in degrees along the arc of a circle which is perpendicular to the prime meridian through Greenwich, England, and parallel to the earth's equator. In Chapter 5, the methods used for the determination of latitude and longitude by reference to the stars and sun on the celestial sphere will be discussed.

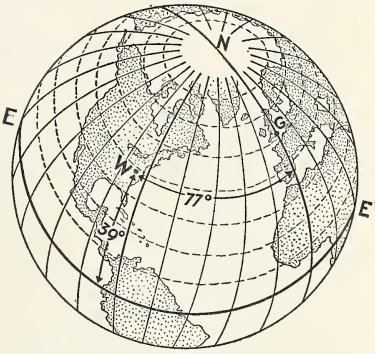


FIGURE 8. THE COORDINATE SYSTEM OF THE EARTH

EE' = *Earth's equator*
NG = *Prime meridian through Greenwich*
W = *City of Washington, D.C.*

In the remainder of this book we are going to read of many applications of the scientific method. As our interpretation of the physical world unfolds, it is hoped that the reader will gradually gain a genuine appreciation of this, the most fruitful method of thinking that has been devised. Scientific thinking has found its widest application in the biological and physical sciences. There remains a tremendous amount of work to be done about the shortcomings of the social and economic structures of mankind. Can this method of thinking be applied to all human problems? Persons who are inclined to answer in the negative need to be reminded that the adoption of this attitude by the biochemist fifty years ago, when investigating the complicated problems of the human body as a machine, would have prevented the discovery of vitamins and hormones. We will learn that science begins not with facts but with problems. It is the function of science to find answers and to make predictions with success. We will find that the methods of science are not narrowly limited.

SUMMARY

1. Scientific thinking is often a very complicated process. Usually some or all of the various steps listed below are followed, though not necessarily in the same order.
   (*a*) Definite recognition of a problem or difficulty.
   (*b*) Collection of a large mass of facts pertinent to the problem, often by experimentation or observation.
   (*c*) Systematization and organization of the fact-material to make possible the induction of generalizations or scientific laws.
   (*d*) The application of the generalizations to new situations, by deduction.
   (*e*) The invention and testing of tentative working hypotheses to devise reasonable explanations of laws and facts.
   (*f*) The evolution of tested and accepted hypotheses into working scientific theories.
   (*g*) The use of scientific theories to serve as a framework for the organization of a body of knowledge and to point the way to further discoveries.
2. Logic, both inductive and deductive, is a necessary part of scientific thinking but all conclusions must be tested by experiment.
3. Induction is the process of deriving a generalization from a mass of fact material.
4. Deduction is the process of applying generalizations to new problems; i.e., to work out a solution of a particular difficulty by reasoning from some accepted generalization.
5. Mathematics is a language which originated out of the needs of daily living.
6. In order to understand our environment and science we need a quantity language, a size language, a position language, and a time language.
7. The physical sciences are based upon a great mass of quantitative fact material.
8. Our language of quantity, using the Hindu-Arabic numerals, employs: (*a*) the digits, 1, 2, 3, 4, 5, 6, 7, 8, and 9; (*b*) the base number 10; (*c*) the principle of position; and (*d*) the concept of the zero, to represent any quantity, large or small.
9. Objective measurements require a system of units made up of a few fundamental standard units and many derived ones.
10. The fundamental standard units are the meter for the measurement of length, the gram for mass, and the mean solar second for time.
11. In the metric system the various derived units are submultiples or multiples of the fundamental standard units and are obtained in a uniform, rational manner. Thus, the fundamental unit can be divided into ten, one hundred, one thousand, or one million equal parts, the parts being indicated by the prefixes *deci*, *centi*, *milli*, and *micro*. A unit a thousand times larger than the fundamental is indicated by the prefix *kilo*.
12. The basic system of weights and measures in this country, including our money system, is the metric system and is under the supervision of the Fed

eral Bureau of Standards. The following conversion factors are very useful when it is necessary to work with both the metric and English systems:

1 in. = 2.54 cm
1 m = 39.37 in.
1 km = 0.62 mile
1 kg = 2.2 lb
1 l = 1.057 liq qt
1 lb = 453.6 g

3. The location of an object or point on a surface or in space requires the use of a suitable frame of reference. A frame of reference may be a plane surface, or a curved surface, as the face of the earth or the celestial sphere. Objects are located on the frame of reference by means of two coordinates which are perpendicular to each other.
4. Quantities above a reference surface, to the "north" or "east" of a coordinate line, or which result from clockwise motion, are called positive. Quantities opposite in meaning to these are considered negative.

STUDY EXERCISES

1. What is the distinction in meaning of the following terms: *fact, knowledge, science, art, feeling*? Give examples.
2. What is the distinction between a scientific hypothesis and a scientific theory? Discuss.
3. The campaign orator and the editorial writer in the daily newspaper often speak scornfully of theories. Is this always justified, or does it reveal a lack of appreciation of what is meant by scientific thinking? Discuss.
4. Discuss two of the important functions of theories in scientific thinking.
5. Was the perfection of the incandescent lamp by Edison the result of chance and keen observation or the deliberate result of the application of a tentative working hypothesis?
6. List as many characteristics as you can to bring out the meaning of the expression "scientific attitude."
7. Place a number to indicate the order in which the following steps are usually followed in scientific thinking:

... Invention of working hypothesis.
... Definite recognition of a problem.
... Induction of scientific laws from a body of organized fact material.
... Collection of a mass of fact material by observation and experimentation.
... Testing of working hypotheses which often lead to acceptance of scientific theories.
... Further application of scientific theories to discover new relationships and make new discoveries.

Reading references for this chapter are on pages 49–50.

3

The Relation of Mathematics to Science[1]

> The time has now come for another Reformation. People must learn to read and write the language of measurement so that they can understand the open bible of modern science.
> HOGBEN [2]

IN THE PREVIOUS CHAPTER, the fundamental importance of facts was emphasized. Physics, chemistry, astronomy, and the other physical sciences differ from the social sciences in that the foundational fact-material is *quantitative* in nature. We can describe an object in *qualitative* or in *quantitative* terms. Quantitative information means knowledge expressed in objective terms of measurement; qualitative information must by its nature be colored with subjective thought and is, therefore, often unreliable. For example, one can say, "Miss Jones is heavy," or "Miss Jones has keen eyesight." These are qualitative statements of fact. The interpretation of these statements by different individuals will vary because of their subjective conceptions as to the meaning of "heavy" and "keen eyesight." On the other hand if one says, "Miss Jones is five feet tall and weighs one hundred and five pounds," or "Miss Jones can read characters one-sixteenth of an inch high at a distance of two feet," quantitative statements are being made. The interpretation of these two statements by different readers should be substantially the same. It should be remembered, however, that even quantitative measurements vary in precision. Every physical measurement is subject to a certain amount of error from the imperfections of instruments and the variability of human behavior. The magnitude of these errors can be progressively reduced, but never entirely eliminated. The smaller the permissible error, the greater the precision of measurement.

Lord Kelvin, one of the greatest scientists of the nineteenth century, expressed the importance of quantitative information in this way:

[1] This chapter is concerned with certain specific though elementary mathematical concepts and skills. With some groups of students, it may be advisable to postpone the study of this chapter until after Chapter 10 has been studied.

[2] Lancelot Hogben, *Mathematics for the Million*. Revised edition. New York: W. W. Norton Company, 1943.

When you can measure what you are speaking about and express it in numbers, you know something about it; when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely in your thoughts advanced to the state of science.

Ratios, limits, frequency, acceleration, density, are not remote abstractions that concern only research scientists. They are necessary for an understanding of this busy workaday world. No one can read the great book of nature, to quote Galileo, "unless he has mastered the code in which it is composed; that is, the mathematical figures and the necessary relations between them."

The Denary Notation

We are going to find that many of the measurements made in science must be expressed in very large or very small numbers. It is necessary to learn the denary notation for representing such numbers. Thus, the diameter of a molecule is about one-hundredth of one-millionth of a centimeter, or 0.00000001 cm. The number of molecules in a cubic centimeter of air is about twenty-five million million million, or 25,000,000,000,000,000,000. The denary character of the metric system has simplified enormously the writing of quantities of this nature and mathematical operations with them. Any number, whether very large or very small, can be concisely written as a small number multiplied by ten raised to a certain power.

$$.0000065 = 6.5 \times 10^{-6}$$
$$870{,}000{,}000 = 8.7 \times 10^{8}$$

The basis for this notation requires a review of the mathematical use of exponents.

Algebraic Operations with Exponents

Multiplication: In the notation of algebra,

$$a^m \times a^n \times a^{-0} = a^{(m+n-0)}$$

This means that the product of the same quantity raised to various powers is the quantity raised to a power which is the *sum* of the exponents.

EXAMPLE: $4^2 \times 4^3 \times 4^{-1} = 4^{2+3-1} = 4^4$

PROOF: $\dfrac{(4 \times 4)\,(4 \times 4 \times 4)}{4} = 4^4$

Division: $a^m \div a^n = \dfrac{a^m}{a^n} = a^{m-n}$

EXAMPLE: $5^5 \div 5^3 = 5^{5-3} = 5^2$

PROOF: $\dfrac{5 \times 5 \times 5 \times 5 \times 5}{5 \times 5 \times 5} = 5 \times 5 = 5^2$

Addition and subtraction: To find the sum of five bushels of potatoes and two gallons of gasoline is an impossibility because the terms are unlike. In like manner, algebraically only *like terms* can be added. Thus,

$$20\,a^m + 5\,a^m - 8\,a^m = 17\,a^m, \text{ and}$$
$$6\,a^m + 20\,a^m + 5\,b^m = 26\,a^m + 5\,b^m$$

EXAMPLE: $30\,a^{1/3} + 6\,a^{1/3} - 30\,a^2 = 36\,a^{1/3} - 30\,a^2$.

Rewriting Fractions with Terms with Exponents

Mathematical simplification often results in rewriting a fraction by bringing the numerator into the denominator, or vice versa. This is a proper procedure, provided the signs of the exponents of the terms which are moved are changed.

EXAMPLES:

$$\frac{a^m}{a^n} = a^{m-n} = \frac{1}{a^{-m}a^n} = \frac{1}{a^{n-m}}$$

$$b^x \cdot c^{-y} = \frac{b^x}{c^y} = \frac{1}{b^{-x}c^y}$$

$$\frac{4^8}{4^3} = 4^{8-3} = 4^5$$

The denary notation for very large or very small numbers is illustrated in the following examples:

$$1.0 = 1 \times 10^0$$
$$10.0 = 1 \times 10^1$$
$$1000.0 = 1 \times 10^3$$
$$1{,}000{,}000 = 1 \times 10^6$$
$$870{,}000{,}000 = 8.7 \times 10^8$$

$$0.10 = \frac{1}{10} = 1 \times 10^{-1}$$

$$0.01 = \frac{1}{100} = \frac{1}{10^2} = 1 \times 10^{-2}$$

$$.000001 = \frac{1}{1{,}000{,}000} = \frac{1}{10^6} = 1 \times 10^{-6}$$

$$.0000065 = \frac{6.5}{1{,}000{,}000} = \frac{6.5}{10^6} = 6.5 \times 10^{-6}$$

To handle very large or very small numbers mathematically by the usual methods of arithmetic is usually a very laborious task. The same operations may be easily carried out in the denary notation by keeping in mind the laws concerning exponents given previously. Some examples:

$$6000 \times 210 = 6 \times 10^3 \times 2.1 \times 10^2 = 12.6 \times 10^5$$
$$0.00012 \times 0.000036 = 1.2 \times 10^{-4} \times 3.6 \times 10^{-5} = 4.32 \times 10^{-9}$$

$$0.00012 \div 0.000036 = \frac{1.2 \times 10^{-4}}{3.6 \times 10^{-5}} = 0.333 \times 10 = 3.33$$

General Procedure. (1) Rewrite all quantities so that the first number s between 1 and 10, followed by 10 raised to the appropriate power; (2) perform all the indicated operations of multiplication or division, putting the decimal in the proper place; (3) determine the proper exponent for the multiplier, 10^x. The problems following are examples of the application of the denary system:

(1) Which is larger, a red blood corpuscle with a diameter of 7.5 microns, or a white blood corpuscle with a diameter of 0.0015 centimeter?

$$1 \text{ micron} = 10^{-6}\text{m} = 10^{-6} \cdot 10^{2} \text{ cm} = 10^{-4} \text{ cm}$$

$$\text{Ratio } \frac{\text{Diameter white corpuscle}}{\text{Diameter red corpuscle}} = \frac{.0015 \text{ cm}}{7.5 \cdot 10^{-4} \text{ cm}} = \frac{1.5 \cdot 10^{-3}}{7.5 \cdot 10^{-4}} = .2 \cdot 10 = 2$$

Hence, the diameter of a white corpuscle is twice that of a red corpuscle.

(2) A molecule has a diameter of about 0.00000001 cm and there are 25 million million million molecules in one cubic centimeter. If it were possible to lay these molecules side by side, how far would they reach?

Diameter of 1 molecule $= 1 \times 10^{-8}$ cm
25 million million million $= 25 \cdot (10^{6})^{3} = 25 \cdot 10^{18}$
Therefore, distance $= (1 \times 10^{-8} \text{ cm})\ (25 \cdot 10^{18}) = 25 \cdot 10^{10}$ cm

$$= \frac{25 \cdot 10^{10}}{(2.5) \cdot (12)} \text{ feet } (2.5 \text{ cm} = 1 \text{ in. and } 12 \text{ in.} = 1 \text{ ft})$$

$$= \frac{25 \cdot 10^{10}}{(2.5)\ (12)\ (5280)} \text{ miles}$$

$$= \frac{25 \cdot 10^{10}}{(2.5)\ (12)\ (5.28 \cdot 10^{3})\ (2.5 \cdot 10^{4})} \quad (25{,}000 \text{ miles} = \text{circumference of earth})$$

$$= .063 \cdot 10^{10-3-4} = .063 \cdot 10^{3} = 63 \text{ times around the earth.}$$

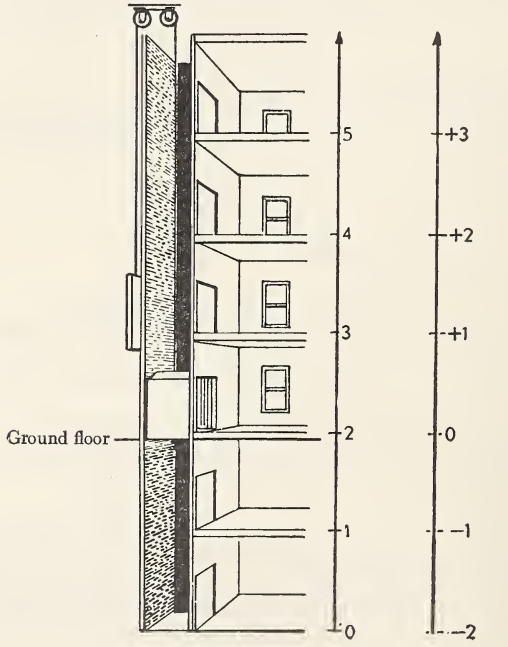
(3) The actual mass (weight) of an atom of hydrogen is known to be $.66 \times 10^{-24}$ gram. How many atoms then of hydrogen are present in one gram of hydrogen?

$$\text{Number} = \frac{1 \text{ g}}{1.66 \times 10^{-24} \text{ g per atom}} = 0.602 \times 10^{24} \text{ atoms}$$
$$= 0.602 \times (10^{6})^{4}$$
$$= 0.602 \text{ million million million million atoms.}$$

The Meaning of Positive and Negative Quantities

The problem of locating a point always requires a designation of direction within the frame of reference. This is often most conveniently done

in terms of plus and minus quantities. As an example, consider an ele vator in a tall building with several sub-basements. Obviously the loca tion of the floor of the elevator could be determined by measuring its eleva tion from the bottom of the shaft, as shown in the diagram. However the usual starting place for using the elevator would be the ground floor Hence, the location of the elevator with respect to the ground floor can better be indicated by using a system of plus and minus quantities in which the *reference* starting point is designated as the zero floor. It is obvious that either method is an arbitrary procedure, adopted for convenience Similarly, the heights of mountains and the depths of the ocean are usually measured from the level of the ocean itself. Elevations above sea leve are considered plus, and elevations below sea level are considered minus Similarly, directions north or east are considered plus; directions south o west are taken as minus. In circular travel, motion in the direction of the hands of a clock is considered plus, and counter-clockwise motion is minus



REFERENCE POINT: Sub-Basement Ground Floor

FIGURE 9. THE USE OF ZERO IN FLOOR NUMBERING

The Concept of Function

One of the most useful of mathematical concepts is that of function. There are many situations where a given quantity changes in value as another quantity changes. A concise statement in the symbolism of mathematics is often employed to express the functional relationship between the two variable quantities. This is a mathematical equation. Consider, for example, the relationships involved in the determination of the perimeters and areas of squares and circles, and of the areas and volumes of cubes and spheres. (Refer to Table 3.)

TABLE 3. SOME COMMON FUNCTIONAL STATEMENTS

	Generalized functional statement	Square	Circle	Cube	Sphere
(P)erimeter	$P = kx$	$P = 4l$ $k = 4$	$P = c = 2\pi r$ $k = 2\pi$	—	—
(A)rea	$A = kx^2$	$A = l^2$ $k = 1$	$A = \pi r^2$ $k = \pi$	$A = 6l^2$ $k = 6$	$A = 4\pi r^2$ $k = 4\pi$
(V)olume	$V = kx^3$	—	—	$V = l^3$ $k = 1$	$V = \frac{4}{3}\pi r^3$ $k = \frac{4}{3}\pi$

Note that the perimeter of a square or circle is a function of a basic dimension l or r. This can be stated in the concise expression, $p = kx$, which can be read, "the perimeter is a function of x," or "the perimeter is *directly proportional to* x." The generalized functional expression for the areas, however, involves the square of the basic dimension, i.e., $A = kx^2$. Similarly, the functional expression for the volume involves the cube of the basic dimension; i.e., $V = kx^3$. In all cases, the first quantity in each equation can be calculated if both the value of k and variable basic dimension x are known. The value of k is determinable from the type of surface or solid involved. (Refer to Table 3.)

The expression of all functional relationships in the precise symbolism of mathematics expedites thought processes. Consider the following examples:

(1) How does the area of a sphere four inches in diameter compare with that of a four-inch cube? This can, of course, be solved by actually calculating the area of both the sphere and cube and making a comparison of the computed areas. A more direct solution is the following:

$$\frac{\text{Surface cube}}{\text{Surface sphere}} = \frac{6l^2}{4\pi r^2} = \frac{6l^2}{4\pi\left(\frac{l}{2}\right)^2} = \frac{6l^2}{\pi l^2} = \frac{6}{\pi} = \frac{1.91}{1}$$

Hence, the surface of the cube is 1.91 times larger than that of the sphere.

(2) How does the volume of a sphere four inches in radius compare wit one of two-inch radius? The simple direct solution is:

$$\frac{V_2}{V_1} = \frac{\frac{4}{3}\pi r_2^3}{\frac{4}{3}\pi r_1^3} = \frac{(2r_1)^3}{(r_1)^3} = 2^3 = 8.$$

Hence, doubling the radius increases the volume 2^3 or 8 times.

Proportions and Proportionality Constants

The equations used in Table 3 represent generalizations long known fron the study of geometry. In tackling unsolved problems involving two o more variables, the functional relationship between the variables must b determined by a careful analysis of experimental data. This often result in equations with proportionality constants. For example, that there is mathematical relationship between the mileage covered by a car and th amount of gasoline put into the tank is common knowledge. This is a example of what is called a *direct ratio* or *direct proportion*. It can be ex pressed mathematically as follows:

d(istance) varies as (is proportional to) g(allons) of gasoline,

or $$d \propto g$$

We then transform this expression into an equality,

$$d = kg.$$

The term k in this equality is called a *constant of proportionality*. Thi expression is capable of a precise mathematical solution if the value of is known in objective terms. The constant k in this problem is obviousl the average mileage per gallon for the car in question. Suppose that, b experiment, it was found that ten gallons of gasoline were consumed fo one hundred and fifty miles of average driving. How far could the car b expected to travel on one hundred and fifty gallons of gasoline?

SOLUTION: $$k = \frac{d}{g} = \frac{150 \text{ miles}}{10 \text{ gal}} = \frac{15 \text{ mi}}{\text{gal}}$$

Then, $$d = kg = \frac{15 \text{ mi}}{\text{gal}} \times 150 \text{ gal} = 2250 \text{ miles}$$

Essentially this same method of procedure is followed in deriving th equation for more complicated functional relationships. For exampl Galileo discovered by experimentation that the distance covered by freely falling object varied as the square of the time. It is also known th an object starting from rest falls sixteen feet the first second. How fa then, should a stone dropped from a tower fall in five seconds?

SOLUTION: $$d \propto t^2, \text{ or } d = kt^2.$$

In this case, $$k = \frac{d}{t^2} = \frac{16 \text{ ft}}{(1 \text{ sec})^2} = 16 \frac{\text{ft}}{\text{sec}^2}.$$

Then, $$d = 16 \frac{\text{ft}}{\text{sec}^2} \times (5 \text{ sec})^2 = 400 \text{ ft}$$

Inverse Proportions. There are many situations where a certain quantity *decreases* in value as another quantity *increases.* These are described as *inverse ratios* or *proportions.* Thus, the volume of a toy balloon, squeezed between the palms of the two hands, becomes less as the pressure exerted by the hands becomes greater. Likewise, the time required to travel a given distance becomes less as the speed of travel increases. Consider the time necessary to travel one thousand miles by airplane at different speeds.

Speed	Time required
100 mi/hr	10 hrs.
200 "	5 "
250 "	4 "
300 "	3.3 "
350 "	2.8 "
400 "	2.5 "

Symbolically, the relationship between speed and time is expressed,

$$V \propto \frac{1}{t}, \text{ or } V = \frac{k}{t}$$
$$S \qquad\qquad S$$

These relationships indicate that the time is halved if the speed is doubled. This is an inverse proportion.

In many situations, a given quantity is found to depend upon more than a single variable, involving both direct and inverse proportions. Thus, the flow of water from tank A to tank B in Figure 10 is found to depend upon two variables, the height (h) of water in tank A, the diameter (d) for a given length (l) of connecting pipe. Experimentally, it was found that the quantity (q) of water flowing into tank B depended upon two variables as follows,

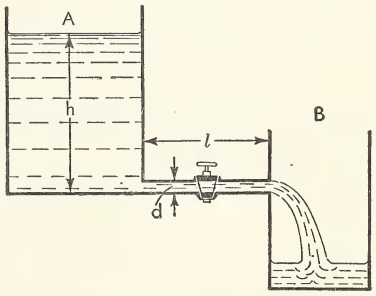


FIGURE 10

(1) $q \propto h$,

and (2) $q \propto d^2$.

These results can be summarized in the single statement $q = k \cdot h \cdot d^2$ after introducing a proportionality constant.

The Meaning of Equations

Equations are of significance because they represent the end product o scientific investigations where a given result is found to depend upon on or more variable factors. In the problem on page 37 involving the rat of flow of water from tank A to tank B, the various relations were dis covered by varying only one quantity at a time. Thus, in a given set o experiments, d and l were kept constant, and q was found to vary with h Then, by keeping h and l constant, q was found to vary as d^2. Thus, ste by step, considering only one variable at a time, the single equation $q = k \cdot h \cdot d^2$ was obtained. In a similar way, every equation used t describe experimental results in science has been obtained by controlle experimentation.

Secondly, we cannot personally verify all the broad general conclusion of science, but we should be able to interpret these conclusions through ou understanding of equations which summarize general principles. Funda mentally, an equation is a concise way of summarizing general principles It expresses the results of observation. To return to the situation de scribed on page 37. Suppose that under a given set of conditions, wate flowed at the rate of five gallons per minute. How much water would flo if the diameter of the pipe was doubled? Since

$$q = k \cdot h \cdot d^2$$

Then,

$$q \propto d^2$$

Hence, the change in the quantity of water delivered will vary as the chang in diameter squared. This means that the new rate of flow will be in creased as 2^2, or 4 times.

SOLUTION: $q_1 = kd_1^2$ and $q_2 = k \cdot d_2^2 = k \cdot 2\,d_1^2$

Then,

$$\frac{q_2}{q_1} = \frac{k \cdot (2\,d_1)^2}{kd_1^2} = \frac{4}{1}$$

Measuring the Distance to Inaccessible Objects

Many situations arise in which it is necessary to measure the distanc to an object where it is impossible to use an ordinary measuring rod or surveyor's chain, as when we want to get the height of a tall building, th distance across a wide river, the distance to a ship at sea, or the distanc to the moon. Here, direct measurement is either difficult or impossibl These distances, however, may be calculated by the methods of trig nometry, which may be considered as a combination of the algebraic co cept of function with geometry. The foundations of trigonometry we

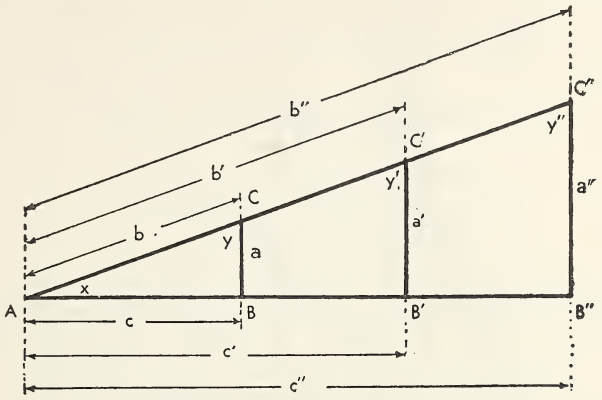


FIGURE 11. SIMILAR TRIANGLES
The sides are equiproportional

aid by the Greek scientist Hipparchus (*ca.* 130 B.C.). With this new mathematical tool, Hipparchus successfully determined the distance to the moon as sixty times the radius of the earth, a relatively accurate result.

As has just been said, trigonometry is a synthesis of algebra with geometry.

The right triangles ABC, $AB'C'$, and $AB''C''$ in Figure 11 with corresponding sides a, a', a'', and b, b', b'', and c, c', c'' are similar. They all have the common angle x, and angles y, y', and y'', which are also equal, since they are all equal to $90° - x$. Now note that certain *ratios* involving the three sides of all three triangles are equal and these ratios can be given arbitrary names,

$$\frac{a}{b} = \frac{a'}{b'} = \frac{a''}{b''} = \text{sine } x, \text{ and}$$

$$\frac{c}{b} = \frac{c'}{b'} = \frac{c''}{b''} = \text{cosine } x, \text{ and}$$

$$\frac{a}{c} = \frac{a'}{c'} = \frac{a''}{c''} = \text{tangent } x$$

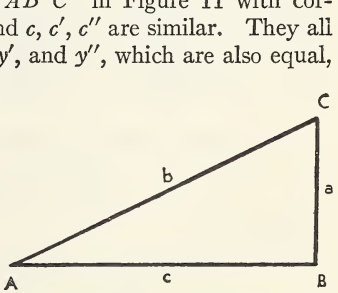


FIGURE 12. THE ANGLES AND CORRESPONDING SIDES OF A RIGHT TRIANGLE

These ratios are called *functions* of x, since they vary in a definite manner as x varies in value from 0 degrees to 90 degrees.

A simple method for the determination of the trigonometrical ratios is shown in Figure 13. AOD is one quadrant of a circle with a radius ten units in length. The resulting angle of 90° is divided into six equal divi-

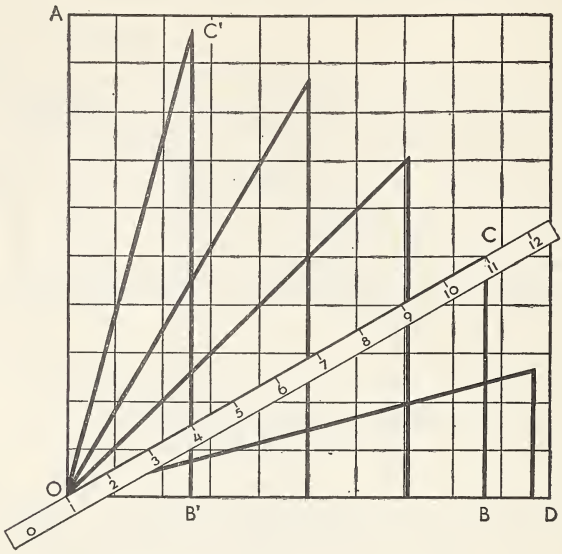


FIGURE 13. DETERMINATION OF THE FUNCTIONS OF ANGLES

sions of 15°. There then can be constructed a series of five right triangle in which the base angle varies from 15° to 75°. With an ordinary ruler it is then possible to measure the lengths of the two legs of each right tri angle. Thus, $BC = 5$ units, $OB = 8.7$ units, $B'C' = 9.6$ units, $OB' = 2.$ units. The hypotenuse of each triangle is ten units in length. Then,

$$\sin 30° = \sin BOC = \frac{BC}{OC} = \frac{5}{10} = 0.50,$$

$$\cos 30° = \cos BOC = \frac{OB}{OC} = \frac{8.7}{10} = 0.87,$$

$$\tan 30° = \tan BOC = \frac{BC}{OB} = \frac{5}{8.7} = 0.58$$

and

$$\sin 75° = \sin B'OC' = \frac{B'C'}{OC'} = \frac{9.6}{10} = 0.96$$

$$\cos 75° = \cos B'OC' = \frac{OB'}{OC'} = \frac{2.6}{10} = 0.26$$

$$\tan 75° = \tan B'OC' = \frac{B'C'}{OB'} = \frac{9.6}{2.6} = 3.70$$

In a similar manner, the trigonometrical ratios for angles of 15°, 45°, 6 or of any other angle can be calculated. By methods of greater precisio

he more accurate values of these quantities as given in Table 4 have been letermined. The definitions for these various functions are as follows, referring to Figure 12.

$$\text{Sine } A = \frac{\text{Side opposite the angle}}{\text{Hypotenuse}} = \frac{a}{b}$$

$$\text{Cosine } A = \frac{\text{Side adjacent the angle}}{\text{Hypotenuse}} = \frac{c}{b}$$

$$\text{Tangent } A = \frac{\text{Side opposite the angle}}{\text{Side adjacent the angle}} = \frac{a}{c}$$

The numerical values of these functions for any angle have been carefully computed and recorded in tables of the trigonometrical functions (ratios). (Refer to Table 4.)

TABLE 4. PARTIAL TABLE OF TRIGONOMETRICAL RATIOS

Angle A	sin A	cos A	tan A
0	0.000	1.000	0.00
$7\frac{1}{2}$	0.131	0.991	0.13
15	0.259	0.966	0.27
$22\frac{1}{2}$	0.383	0.924	0.41
30	0.500	0.866	0.58
$37\frac{1}{2}$	0.609	0.793	0.77
45	0.707	0.707	1.00
$52\frac{1}{2}$	0.793	0.609	1.30
60	0.866	0.500	1.73
$67\frac{1}{2}$	0.924	0.383	2.41
75	0.966	0.259	3.73
$82\frac{1}{2}$	0.991	0.131	7.56
90	1.000	0.000	∞

The usefulness of trigonometry for the determination of distances to inaccessible objects will be illustrated by two examples.

EXAMPLE 1. An aeroplane climbs steadily at an angle of $22\frac{1}{2}$ degrees. After it has gone two miles, measured along the ground from the starting point, what is its elevation?

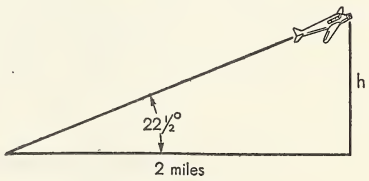


FIGURE 14

SOLUTION: The elevation is the vertical height in Figure 14. By the definition of a tangent,

$$\tan 22\tfrac{1}{2}^\circ = \frac{h}{2 \text{ mi}} = 0.41$$

The numerical value of the tangent is obtained from Table 4.

Then, $h = (2 \text{ mi})\ (.41) = .82 \text{ mile} = (.82)\ (5280) = 4330 \text{ feet}$

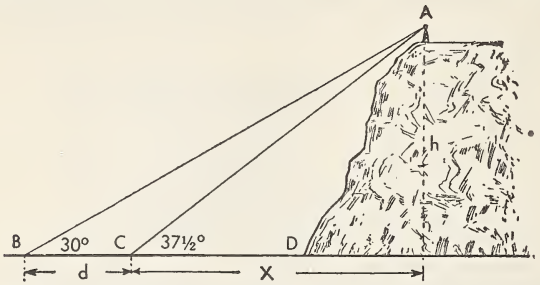


FIGURE 15. THE TRIGONOMETRICAL METHOD OF MEASURING HEIGHTS

EXAMPLE 2. A somewhat more difficult problem is involved in the determination of the height of the top of the lighthouse above the beach shown in Figure 15. A represents the edge of a cliff high above the beach BCD below. At C, the altitude of A above the beach line was observed to be $37\frac{1}{2}°$, while at B, the altitude was 30°. The distance between B and C was found to be one hundred and fifty feet. Now recall the definition for the tangent of an angle: the ratio of the side opposite the angle to the side adjacent to the angle. From this, it follows that,

$$\tan 30° = \frac{h}{d+x} = \frac{h}{150+x} = 0.58 \qquad (1)$$

$$\tan 37\tfrac{1}{2}° = \frac{h}{x} = 0.77 \qquad (2)$$

From equation (1),

$$h = 0.58\ (150 + x)$$
$$= 87 + .58\ x$$

Substituting this value of h in equation (2), we have:

$$\frac{87 + .58\ x}{x} = 0.77,$$

or $$87 + 0.58\ x = 0.77\ x,$$

and $$0.77\ x - 0.58\ x = 87, \text{ or } 0.19\ x = 87,$$

and $$x = \frac{87}{0.19} = 457.9 \text{ feet.}$$

Then, substituting this value of x in equation (1), we have:

$$h = (150 + 457.9)\ (.58) = 607.9\ (.58)$$
$$= 352.6 \text{ feet.}$$

The general process of finding the distance to inaccessible objects using the methods of trigonometry is called *triangulation*. The appropriateness

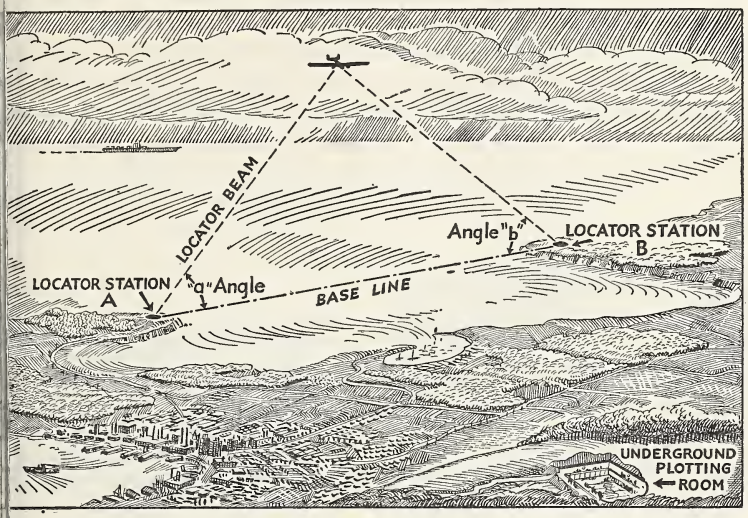


FIGURE 16. LOCATING AN AEROPLANE BY TRIANGULATION

the term is brought out in the use of locator stations to detect distant eroplanes. (Refer to Figure 16.) The locator stations can "spot" a stant aeroplane visually, or by relying upon sound waves or radio waves hich are detected by a suitable "pick-up" and amplifying system. *potting* an aeroplane means in this case measuring the angle made by a ne from the aeroplane to the locator station and the base line between ne two locator stations. The length of this base line is known accurately. he data from at least two locator stations, after being telephoned to a otting station, are all that is needed to locate the aeroplane. In the otting station, a triangle is constructed from the length of the base line nd the angles a and b. The various needed dimensions of this triangle nd the location of the airplane, can then be calculated by the use of trigo- ometry or by drawing a triangle to scale, using a suitable scale for the ngth of the base line.

ne Notations for the Power and the Root of a Number

It is often necessary to multiply a quantity by itself. The exponential otation is the briefest way to indicate this operation. For example:

$$32 = 2 \times 2 \times 2 \times 2 \times 2 = 2^5$$

$$1{,}000{,}000 = 10 \times 10 \times 10 \times 10 \times 10 \times 10 = 10^6$$

$$0.00010 = \frac{1}{10000} = \frac{1}{10^4} = 1 \times 10^{-4}$$

The reverse operation is called *extraction of the indicated root* of a number. The sixth root of 64, written $\sqrt[6]{64}$, is that number which when multiplied by itself six times will give the number 64. In this case, $\sqrt[6]{64} = \sqrt[6]{2^6} = 2$. Students are often puzzled as to the best way to proceed in problems of this sort. Students who have not had advanced courses in mathematics should realize that there is one method which can always be used — the method of inspection and successive approximations. Suppose it were necessary to get the cube root of 18, or $\sqrt[3]{18}$ = what value? The starting point is to realize that the $\sqrt[3]{8} = 2$ and $\sqrt[3]{27} = 3$; hence, we can assume that the desired value will be closer to 3 than to 2, say 2.7. Then, by actual trial,

$$2.7 \times 2.7 \times 2.7 = 19.7.$$

Hence 2.7 is a little too large. Suppose we try 2.5:

$$2.5 \times 2.5 \times 2.5 = 15.6,$$

which is a little too small. We then can "pinch off" a better value by a little intelligent and persistent application. We can systematize our efforts by tabulating our results:

$2.6^3 = 17.6$	Too small
$2.65^3 = 18.6$	Too large
$2.62^3 = 17.98$	A little small
$2.63^3 = 18.19$	A little too large

By this method of approximation, we now know that $\sqrt[3]{18}$ is a little larger than 2.62 and a little smaller than 2.63. If it is necessary to have a more accurate value, the method of approximation can be carried even farther.

Extension of Human Perception

The extent to which science has unraveled the pattern of the universe is significantly indicated by the range in size of various objects or distances.

Table 5. Range of Sizes in the Universe

	English Units	Centimeters
Distance to farthest visible stars	130,000,000 light years	1×10^{26}
Distance to nearest stars	4.3 light years	4×10^{18}
Distance to sun	93,000,000 miles	1.5×10^{13}
Distance to moon	240,000 miles	4×10^{10}
Diameter of earth	8000 miles	1.3×10^{9}
Empire State Building	1284 ft	4×10^{4}
Height of a person	6 ft	180
Common unit of length	1 inch	2.54
Thickness of sheet of paper		8×10^{-3}
Diameter red blood corpuscle		7.5×10^{-4}
Wave length visible light		6×10^{-5}
Wave length X-rays		1×10^{-6}
Diameter of an atom		1×10^{-8}
Diameter of electron		1×10^{-13}

which have been measured. Modern experimental procedures have enormously extended the range of human perception. The astronomer, for example, has built telescopes that can photograph a spiral nebula in Andromeda, which is so far away that if it should cease to exist today as a result of some catastrophic event, the result would not be known on the earth until after 900,000 years. The enormous range in size of various objects in our universe is indicated in Table 5.

The molecule is so small that if 250,000,000 of them could be laid side

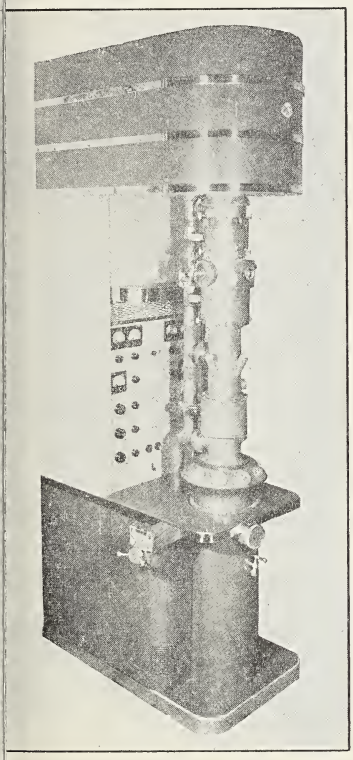


FIGURE 17. THE ELECTRON MICROSCOPE

A help in solving many problems in all fields of science.

(*Courtesy of Radio Corporation of America*)

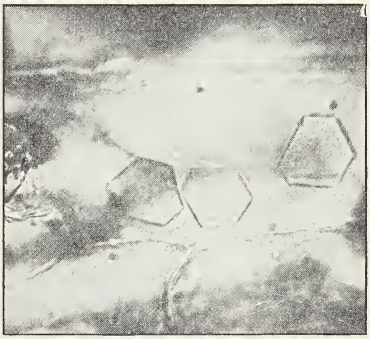


FIGURE 18. THE STRUCTURE OF A TOBACCO PLANT DISEASE INSIDE A LIVING PLANT CELL

(*Courtesy of Dr. Helen Purdy Beale, Boyce Thompson Institute*)

FIGURE 19. PERMANENT REPLICA OF A SNOWFLAKE UNDER A HIGH POWER MICROSCOPE

(*Courtesy of General Electric Company*)

by side, they would reach only an inch. These measurements in many cases are beyond our comprehension, yet they represent real measurements not figments of the imagination. These measurements are based upon sound scientific principles coupled with skilled experimental technique with the results always interpreted in the precise language of mathematics. Many of these achievements will come up again for study in later chapters.

The electron microscope is a recent example of the ability of the scientist to extend the limits of human perception. (Refer to Figure 17.) Previously the finest microscope could not magnify an object more than about two thousand times. The magnifying power of the electron microscope may be fifty times greater, or one hundred thousand. It is by the development of machines such as this that scientists hope to conquer certain diseases caused by organisms too small to be detected with ordinary microscopes. In Figures 18–20 the photographs show what can be accomplished with modern microscopes, including the electron microscope.

The ordinary microscope functions with a beam of ordinary visible light; the electron microscope, with a beam of electrons. The manner of travel of light in an undulatory motion with a definite wavelength will be presented in Chapter 44. The wavelength of a beam of electrons is very small in comparison with that of light, and the greater resolving power of an electron microscope is dependent upon that property. The small particles in Figure 20 can be seen only as a white smoke when viewed by the unaided eye. In the field of an ordinary microscope, these particles are invisible. But note that the tiny particles in the magnesium oxide smoke, for example, can be "seen" as cubes only 1.0×10^{-6} centimeters on a side. The total magnification is about 100,000 times. With this instrument the protein molecules which are responsible for certain virus diseases have been photographed. (Refer to Figure 18.)

In a later chapter reference will be made to the recently dedicated 200-inch reflecting telescope on the top of Mount Palomar in California. This is expected to penetrate into space so far that light originating there and traveling 186,000 miles per second will require over 500,000,000 years to reach the earth. One of the important functions of this volume is to present those principles of science which have made possible the instruments now so marvelously used to extend human perception and to show how the information thus obtained has influenced our modes of thinking and living.

SUMMARY

1. The denary notation is exclusively used in science for writing very large or very small numbers.
2. An expression in symbols which indicates how one quantity changes in value as another quantity changes is known as a function. Functional quantities which contain proportionality constants are very common. The student

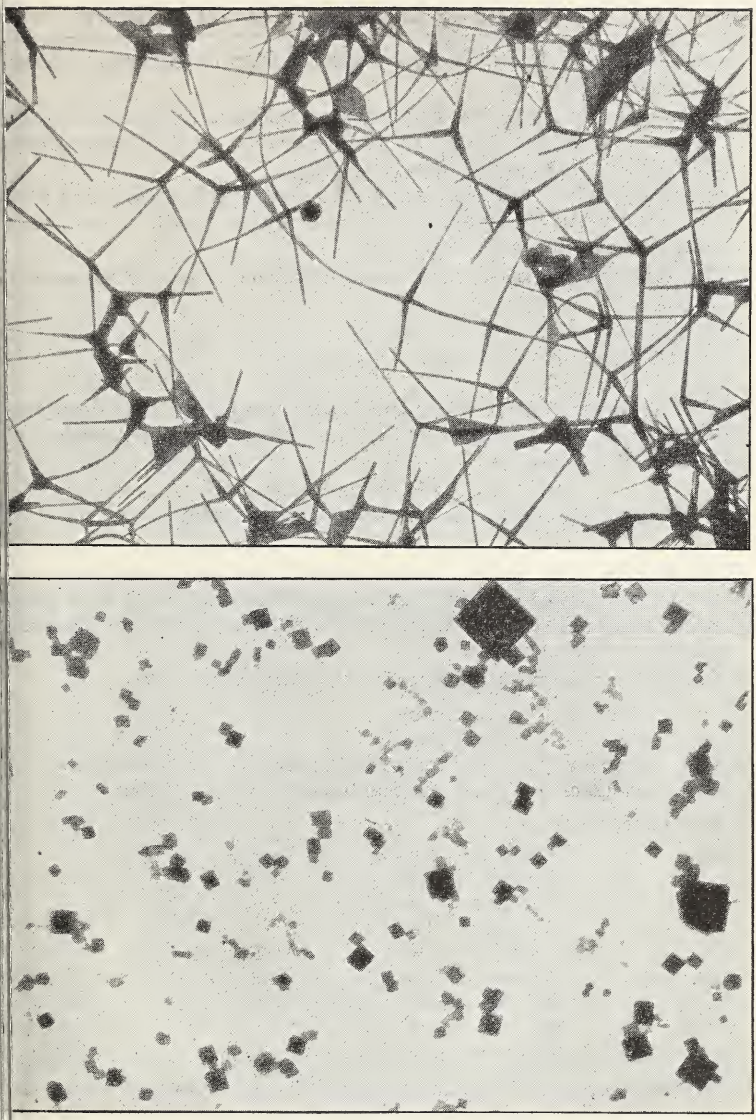


FIGURE 20. PHOTOGRAPHS MADE WITH AN ELECTRON MICROSCOPE

These photographs show how particles as small as one millionth of an inch can be made visible for study. These were made with particles of smokes of zinc oxide (above) and of magnesium oxide (below). The apparently structureless particles are shown to exist as definite geometrical shapes under a magnification of 25,000 times. (Courtesy of Battelle Memorial Institute)

urged to learn to identify a direct proportion or an inverse proportion from its mathematical form.

3. Equations to express scientific principles are important, because: (*a*) they represent the end-product of scientific investigation, and (*b*) they summarize in concise form general scientific principles.
4. The branch of mathematics which combines arithmetic, algebra, and geometry is trigonometry. By means of trigonometry it is possible to measure the distance to inaccessible points.
5. The student should master the meaning of the sine, cosine, and tangent of an angle.

STUDY EXERCISES

1. With the digits, the principle of position, and the zero as in the denary system, 2012 would be a notation for what quantities in the quinary, duodecimal and sexagesimal systems?

   2012 = ... in the quinary system
   = ... in the duodecimal system
   = ... in the sexagesimal system

2. Many students of numbers believe that a duodecimal system would have decided advantages over our present decimal system. From what standpoints would this be true? What are some of the reasons that such a change probably will not be made?
3. Classify the following as fundamental (*f*) or derived (*d*) units.

.... decimeter	.... gram	.... inch
.... meter	.... pound	.... gallon
.... kilogram	.... square centimeter	.... microgram
.... milligram	.... cubic centimeter	.... dollar

4. Find the sum of:

(*a*)	4 dollars	=	
	7 dimes	=	
	18 nickels	=	
	36 pennies	=	
	4000 mills	=	Sum = ...
(*b*)	3 meters	=	
	2 decimeters	=	
	22 centimeters	=	
	108 millimeters	=	Sum = ...

5. Our money system is a metric system and the basic system of weights and measures in the United States is the meter-gram-second system. How can you account for the widespread use of the awkward English system of weights and measures in this country?
6. What arguments can be advanced for abolishing the foot-pound system in this country? What arguments can be advanced in favor of retaining this system?

7. (*a*) Express a body weight of 150 pounds in kilograms, in grams, and in milligrams.
(*b*) How many millimeters in a kilometer?

8. Express the following quantities in the denary notation:

(*a*) 2,200,000 (*b*) 7,829,000,000

(*c*) $\frac{425000}{1800} =$ (*d*) $\frac{.00012}{.0000040} =$

9. A certain photographic film measures 6.5 cm × 9 cm. What is its size in inches?

0. The blood of a normal person contains about 5,000,000 red blood corpuscles per cubic millimeter. How many red blood corpuscles would there be in 500 cm^3 of blood (about a pint)?

1. During a gas-consumption test, a certain car was found to travel 270 miles on 15 gallons of gasoline. How many gallons would be needed at this rate of consumption to travel 1500 miles? Read page 36 again before attempting a solution.

2. At a large banquet the dessert was to be slices of ice cream cut from "bricks." The caterer planned to serve each person a portion q. The size of q (in terms of fractions of a single brick) will depend upon two variable quantities, the number (n) of bricks available and the number of persons (p) to be served. Which of the following is the correct expression for the size of each portion?

(*a*) $p \propto \frac{n}{q}$ (*b*) $q \propto \frac{n}{p}$ (*c*) $q \propto \frac{p}{n}$ (*d*) $q \propto np$.

3. Refer to Figure 13. Estimate the length of the "side opposite" and the "side adjacent" for angles of 15°, 45°, and 60°. Calculate numerical values for the sine, cosine, and tangent for each of these angles. Record your data in the following table.

Angle	Side adjacent	Side opposite	Sine	Cosine	Tangent
15°	....	....	....	....	....
45°	....	....	....	....	....
60°	....	....	....	....	....

How do your values compare with those given in Table 4? How can you account for differences?

FOR FURTHER READING

. Andrews, F. E., *New Numbers*. New York: Harcourt, Brace and Company, 1935.

The origin of number systems is discussed in Chapter 2. Much of the rest of this interesting volume is concerned with the advantages of the duodecimal number system over our present denary system.

2. LOGSDON, M. I., *A Mathematician Explains.* Chicago: University of Chicago Press, 1935.
An interesting presentation for the general reader of the significance of mathematics and the nature of its various branches. The following chapters are especially recommended: Chapter 2 on the origin and nature of number systems; Chapter 4 on geometry and trigonometry; Chapter 5 on frames of reference and the concept of function; Appendixes A and B on direct and indirect proportion and the use of exponents.

3. NORTHROP, F. S. C., *The Logic of the Sciences and the Humanities.* New York: The Macmillan Company, 1947.
Shows how science should work in the social sciences.

4. HOGBEN, LANCELOT, *Mathematics for the Million.* Revised edition; New York: W. W. Norton Company, 1943.
A book which had an immense sale when it first appeared, helping many to gain a real appreciation of the social and scientific significance of mathematics. The following chapters are recommended reading: Chapter II on the early history of mathematics; Chapter VI on the uses of trigonometry; and Chapter IX on graphs.

5. THORNTON, JESSE E., *Science and Social Change.* Washington, D.C.: The Brookings Institution, 1939.
This volume is an eloquent plea for the widespread use of the scientific method for the solution of social and economic problems. The following passages will be found especially worth reading: the relation of science and modern civilization, pages 21–35; science as method and not as material, explained by the philosopher Karl Pearson, pages 56–68; a discussion by George A. Gray on the significance of the widespread application of the scientific method, pages 478–495; the nature of the great problems confronting the American people and awaiting a scientific solution, as discussed by Karl T. Compton, pages 496–512.

6. DAMPIER, WILLIAM, *History of Science.* New York: The Macmillan Company, 1932.
A thorough discussion of the meaning of scientific thinking such as the nature of scientific logic, the relation of science to mathematics, and the meaning of scientific laws, pages 445–468.

7. HASLETT, A. W., *Unsolved Problems of Science.* New York: The Macmillan Company, 1935.
Points out in a very challenging way some of the many important problems that still remain to be solved by the application of scientific thinking.

8. DEWEY, JOHN, *How We Think.* Boston: D. C. Heath and Company, 1934.
An elementary treatise on logic by one of America's great philosophers. Chapter XIII deals with empirical and scientific thinking, inference by induction and deduction, and the meaning of truth.

9. CHAPMAN, F. M., and PAUL HENLE, *The Fundamentals of Logic.* New York: Charles Scribner's Sons, 1933.
The methodology and the articles of faith of the sciences are discussed in Chapters XIII and XIV.

4

A First Look at the World

N OLD FAIRY STORY tells of several captive brothers and their first glimpse
f the world. Led by a younger brother, they climbed a hill and saw
ıe clouds, the distant rivers, the birds, the trees of the forest, and the
ıimals that moved among them. They were all fascinated by the
eauty of this bird's-eye view. The rest of their story concerns itself
ith what they found, when, on the next day, they came down to ex-
ıine things more closely. The present story of the physical world fol-
ws a similar plan.

ıe World as We See It

Our information about the world comes through the five senses, and of
ıese, the sense of sight contributes most to man's view of the world of
ıings and events. When we attempt to discover some point at which
e can begin our study, our first impression is that there is little order
ıd that our world is filled with buildings, clouds, trees, telephone poles,
ıairs, lamps, dogs, human beings, automobiles, and a thousand other
ıings. They strike us as being separate and distinct, that is, as being
ıconnected and as occupying a definite space. Experience teaches that
human foot cannot occupy the same space as a rock at the same time.

In general, visible things are of different shapes and forms. Some are
ke air, and are characterized as *gaseous*. Others are compact and
quid, like water. Finally, such objects as stones are hard and resistant
lids. Many things, moreover, if observed for any length of time, are
ound to change position; that is, to *move*. These and all other changes
ınstitute *events*. A cow moves slowly, a dog faster, and a car more
ıpidly than either. Telephone poles, chairs, books, stones, retain the
ıme position unless they are pushed. Their motion, like all other motion,
ınstitutes a change, or event. There are myriad changes and innumer-
ıle events in evidence all around us. Life depends upon them; a person
ıanges the position of his feet to walk, of his hands to work, of his eyes to
ıserve, of his mouth and throat to talk. Food undergoes changes in
ssimilation. Trees, shrubs, and grass also change. They start from

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seeds and grow day by day, utilizing the sun, air, and moisture in thei growth. Looking upward toward the sky, we observe other changes — of the sun, the moon, and the stars. There are changes of season an changes of weather. A jumble of events staggers the imagination whe we try to arrange them. The human mind is forever seeking order. Ou first impression of our environment is bewildering. Only by applying careful and systematic method can we learn to understand the visibl world.

The first essential in scientific study is careful observation of assemble facts. Events then reveal themselves not as haphazard but as occurrin with uniformity according to principles which we can discover. Rainfa is brought about by clouds. The rain turns into snow if it is cold enough this occurs most frequently in the winter. In the spring, the trees hav green leaves, which in the autumn turn yellow and red, and fall. A animals and plants come from seeds or eggs; living things are born, grow reproduce their kind, and die. The sun appears and disappears once eac day. There is a new moon every twenty-nine days. The clusters of sta overhead, moving slowly, change regularly with the seasons.

Things, however, are not always what they seem to be. In scienc seeing is not always believing, for many things occur that are invisible t the eye, though detectable by instruments. All is not gold that glitter of which adage one of the most familiar examples is fool's gold. A pie of wood burns, vanishes, and leaves behind only a small amount of as a fraction of its former weight. The physical world and the changes occu ring in it must first be described and carefully measured, and the immed ate environment closely explored, to prevent false deductions.

A good illustration that things are not always what they seem to be the first glimpse of the sky overhead. During the day it appears as blue film, spherical in shape and meeting the earth at a line which called the *horizon*. On this blue film the sun appears to rise in the ea and set in the west; the next day the sun is seen to rise in the east agai hence the obvious conclusion is that the sun travels around the eart Yet everyone is taught at an early age that it is the earth which revolv around the sun, spinning about its axis once every day while traveling this circle. When the sun sets, a countless multitude of bright poin called *stars* appear in the sky. The stars also rise in the east, pass acro the sky, and set in the west. The same stars appear in the east again t next evening. Most stars appear as shining points of light; this light unsteady, and hence stars are said to twinkle. There are nine brig celestial objects, however, which shine with a steady light and who movements are different from those of the other stars: although travelin daily, like the other stars, from east to west, their *relative* position amo the stars in the sky also changes from day to day, so that, as the mont pass, most of them appear to be at the same time moving slowly fro

west to east and, after undergoing a reversal of their motion, from east to west. Inasmuch as these heavenly bodies do not appear to keep their positions among the other stars, but have a tendency to wander, they are called *planets* (wanderers).

The Solar System

The solar system is composed of the sun as the central body around which revolve these nine planets accompanied by twenty-eight moons; several thousand tiny planets, called *planetoids*, together with some comets and an immense number of meteors, make up the rest of the family.

Figure 21 shows diagrammatically the members of the solar family. Though the diagram is not drawn to scale, it shows that the planets fall into two groups. The first four, smaller and closer to the sun, are called *inner planets;* the *outer* ones, with the exception of Pluto, are larger. The inner planets are represented in the diagram as dots on circles representing the paths or orbits which they are assumed to follow in their revolution about the sun. As their distance from the sun increases, the time required for them to make a complete revolution also increases. For example, the earth completes its revolution in one year, Mercury in eighty-eight days, Jupiter in 11.9 years, and Pluto in 248 years.

A fuller explanation of the motions of the planets is given in Chapter 16. For the present we must center our attention on the earth and learn to use the tools of science in observing, describing, and correlating the facts near at home before we proceed to explore objects out in space.

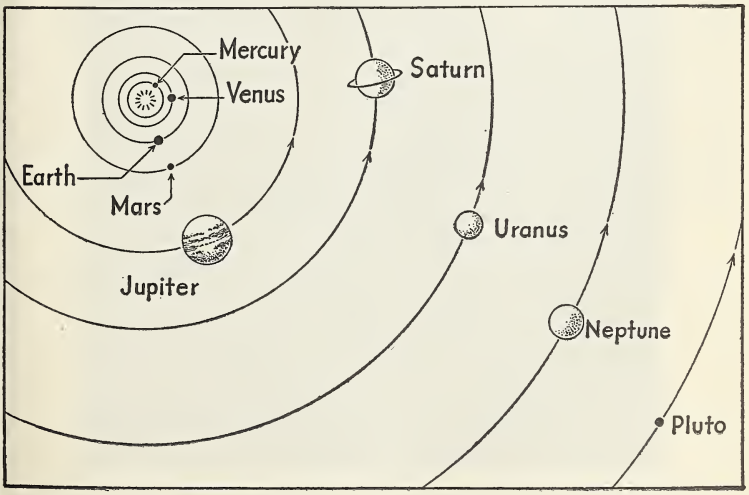

FIGURE 21. THE SUN AND THE PLANETS

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The Shape of the Earth. The earth is assumed to be roughly spherical in shape. This concept is so familiar to the student that its repetition here may seem superfluous. Analysis of the statement, however, reveals that at this point we are only making the assumption that the earth is round, unsupported by any evidence. Without evidence it is inadequate for our purposes here to accept the fact which we have heretofore taken for granted that the earth is round, rotates on its axis, and revolves in an orbit about the sun. We must examine the evidence which supports this concept before accepting it.

Often, in fact, throughout this text the student will encounter similarly familiar facts of this kind which must be reinspected from a critical point of view. Progress in education consists not so much in learning new facts as acquiring the ability to understand knowledge we already possess.

Evidence for the Curvature of the Earth. The casual observer does not trouble much about the shape of the earth. If he believes that the earth is a sphere, it is because he has read or heard that it is so. If he relies on his own experience he, like most of the ancients, will arrive at a vague conception that the earth has a flat "pancake" shape dotted with valleys,

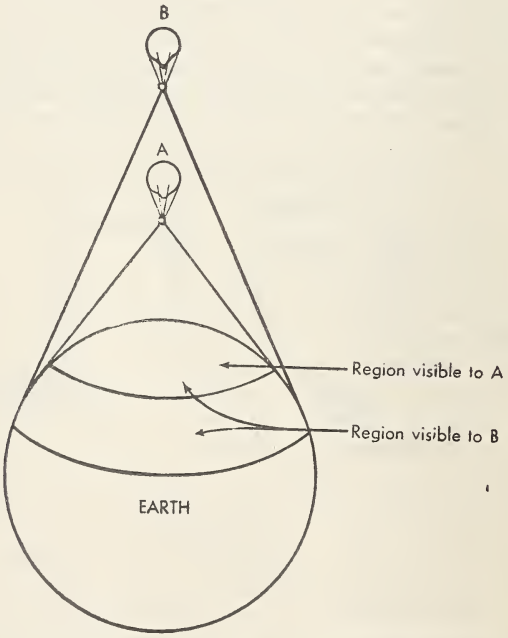


FIGURE 22. A PROOF OF THE CURVATURE OF THE EARTH

ridges, and mountains. But the systematic observer will be able to cite a number of events which cannot be explained on any other assumption except that the earth has a curvature.

Watching a ship traveling away from us is not an uncommon experience. At first, the whole ship is in sight, but after some time only the upper parts of the ship — the funnel and the masts — are visible. Looking through a telescope as the ship is receding in the horizon shows the ship vanishing slowly with the lower part first. If the earth were flat, the ship would become smaller and smaller, but would remain wholly visible, though the outline might be blurred. But if the earth is curved, the disappearance of the receding ship is explained.

Observations from airplanes and balloons offer additional evidence of the curvature of the earth. Consider, for example, the two balloons *A* and *B* in Figure 22. If the earth were flat, all would be equally visible from *A* and *B* and the visibility would be limited by the observer's power of vision. But if the earth were curved, then the region visible from balloon *B* would be greater than that visible from balloon *A*. The experience of observers is that from an altitude of a thousand feet the radius

FIGURE 23. ANOTHER PROOF OF THE CURVATURE OF THE EARTH
The earth casts a circular shadow, as seen in a partial eclipse of the moon

(*Photo by Applied Physics Laboratory of the Johns Hopkins University/Navy*)

FIGURE 24. A FURTHER PROOF OF THE SPHERICITY OF THE EARTH

Curvature of the earth as photographed from a V-2 bomb at an altitude of 65 miles (October 24, 1946, at White Sands, New Mexico). The distance of the camera from the horizon was theoretically 730 miles. If there had been an observer on the rocket, he could have seen approximately 1,630,000 square miles of the earth's surface.

of visibility is limited to about forty miles, but at an altitude of forty thousand feet the radius of visibility is about two hundred and fifty miles.

One of the earliest proposed proofs of the curvature of the earth was made by Aristotle, whose arguments were essentially those which we employ today. The shadow of the earth, seen upon the moon during a lunar eclipse, when the earth is between the sun and the moon (see page 55), is essentially circular. The picture shown in Figure 23 is taken from a photograph of a lunar eclipse and is exaggerated in order to indicate sharply the edges of the shadow.

The most recent proof of the curvature of the earth is shown in the photographs of the earth's surface made during stratosphere flights and by means of cameras attached to V-2 bombs. Figure 24 shows the curvature of the earth as photographed from a V-2 bomb at an altitude of 65 miles.

The Size of the Earth

If the earth is circular like a globe, then it should be possible to measure the circumference by measuring the length of one degree and then multiplying it by three hundred and sixty, since that is the number of degrees in a circle. The diameter, radius, area, and volume can be easily calculated by means of the formulas which give the various relations of the sphere as shown on page 35.

The method used for measuring the length of a degree of an arc is the same as that used by Eratosthenes (*ca.* 225 B.C.), librarian of the great museum at Alexandria. The principle of the method is illustrated in the following example: Two cities, *A* and *B*, are situated 690 miles apart, as indicated in Figure 25. The linear distance has been accurately measured by means of a chain used in surveying. Observers at these two cities agree to take observations on a certain star at the same time, say 10 P.M. on June 29. Observer at *A* points his telescope at the star agreed upon,

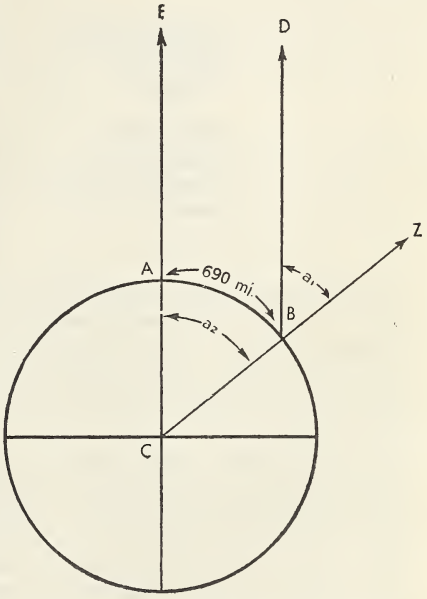


FIGURE 25. MEASURING THE EARTH'S CIRCUMFERENCE

Method used by Eratosthenes, 235 B.C.

which is directly overhead. At the same moment, observer at B points his telescope at the same star and measures the angle a_1 formed by the line to the star, BD, and the vertical, CBZ, which is the direction taken by a plumb line. Now, the lines CAE and BD are in effect parallel, since they both point to a star so far from the earth that the departure from exact parallelism cannot be measured. Since the two lines are parallel, the two angles a_1 and a_2 are equal. The value of angle a_1 in the present example was found to be 10° of arc. The linear distance for 10° is 690 miles, and therefore the length of 1° of arc is $\frac{690}{10}$, or 69 miles. Having obtained the linear length of 1° of the earth's sphere, the circumference is found by multiplying the linear distance of 1° of arc by 360; hence the earth's circumference is

$$69 \times 360 = 24{,}800 \text{ miles.}$$

The length of a degree of arc is not the same in various parts of the earth, since the earth is flatter near the poles. The difference, however, is not very great: about 69.4 miles at the pole, and 68.7 at the equator. The diameter and radius are obtained from the above figures as follows:

Equatorial radius.....	3,963.34 miles
Polar radius.....	3,949.99 miles
Difference.....	13.35
Mean radius.....	3,958.82 miles
Mean diameter ($2r$)...	7,917.98 miles
Circumference ($2\pi r$)..	24,875.126 miles
Area ($4\pi r^2$).....	196,914,800
	or about 197×10^6 square miles.

Other important data concerning the earth are its mass, volume, and density. By the term *mass* is meant the quantity of matter, which is measured in pounds or grams; the *volume* designates the amount of space occupied by a body, and is measured in cubic feet or cubic centimeters; the term *density* designates the ratio of the mass divided by the volume of a body, and expresses the amount of mass in one unit volume. The density of water is 1 gram per cubic centimeter; the density of iron is 7.8 grams per cubic centimeter, and therefore any volume of iron is 7.8 times heavier than an equal volume of water. The method by which the mass of the earth is measured is discussed in a subsequent chapter. The value obtained for the earth is 6×10^{21} metric tons, or 5.97×10^{27} grams. For comparison, a ton may be taken as 1×10^6 grams. An average sun or star represents about 1×10^{32} grams, while the largest star is estimated at 1×10^{35} grams. The volume of the earth is obtained from the formula for the volume of a sphere ($V = \frac{4}{3}\pi r^3$). The value obtained is 259×10^9, or

259,000 million cubic miles, or 1.08×10^{27} cubic centimeters. The density, M/V, is obtained by simple division:

$$\frac{5.97 \times 10^{27}\ \text{g}}{1.08 \times 10^{27}\ \text{cm}^3} = 5.5 \text{ grams per cubic centimeter,}$$

or 5.5 times that of water.

Motions of the Earth

Our examination of the earth has given us some definite knowledge about its form and size and also the methods by which this knowledge can be checked. It is now desirable to examine the facts indicating that the earth moves.

Our everyday experience does not give any direct observable evidence of this motion; instead, it is the sun and the other heavenly bodies that appear to move. The sun appears to rise and set, causing an alternation of day and night. The stars, if watched for a few hours, appear to slide, so to speak, upward overhead or downward to the horizon. In order to explain this apparent behavior we can make two assumptions. First, we can assume the obvious hypothesis, long held to be true, that the sun and the stars are attached to the inner surface of a huge celestial sphere which turns around daily. Second, we can propose what is today assumed to be true: that the earth rotates on its axis in twenty-four hours and thus exposes alternately each of its hemispheres to the sun.

This second hypothesis raises a question that should be answered before we examine the evidence in its favor. If the earth is moving, we may well ask, why are we not aware of its motion? The answer is simple. By motion we understand the change of position of an object with reference to another. If the earth moves, everything on the earth moves with it; unless there were a reference object that did not move, or else moved along with a different speed, we could never perceive this motion. The motion of an automobile or a train is known by the passenger because of the vibrations and jerks, and the sight of objects which are passed on the way. If the automobile or train could be made to run without the least vibration, and if there were no windows on the cars, the passenger would be unaware of motion.

Evidence for the Earth's Rotation. The earth is assumed to turn about on an imaginary axis which passes through the earth itself and reaches the surface at two points called the *poles*. The midpoint on the surface of the sphere between the north and south pole is the *equator*. If we stick a colored pin or spot of paper on the equator of a small globe spinning on its axis, then move the spot upwards or downwards to various positions nearer one of the poles, and finally put it on the pole itself, it will be evident that the spot travels its greatest distance at the equator, the length of its revolutions become shorter as it approaches the pole, and when on the pole it

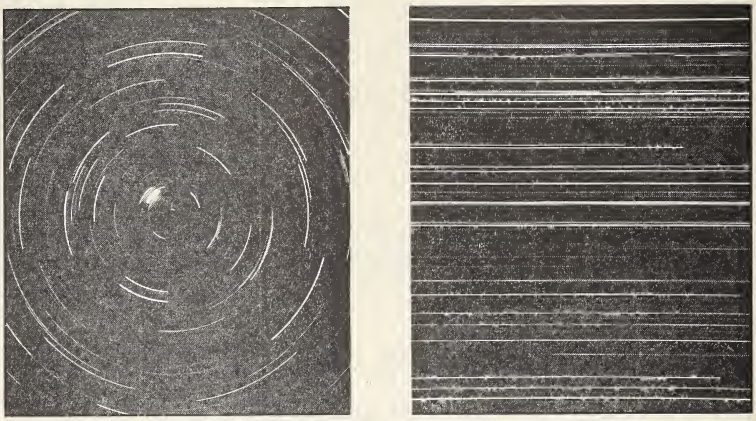


FIGURE 26. STAR TRAILS AROUND THE POLE AND AT THE EQUATOR
(*Yerkes Observatory, Courtesy of the University of Chicago Press*)

does not travel at all, but simply rotates upon its own axis. Now, if we were to attach the base of a pencil to the globe, so that the point aimed out straight from the globe and met a piece of white cardboard held within its reach, the pencil would draw a straight line when affixed to the equator, and a series of smaller and smaller circles as it approached the pole.

If we are right in assuming that the earth rotates on its axis, then stars observed directly overhead at the equator should appear to move in straight paths, but those observed near the poles should seem to have circular courses. By using a camera, the equivalent of the pencil in our experiment with the small globe, allowing several hours for each exposure, we can ascertain that this is true. In Figure 26 are photographs of typical "star trails."

Photographs such as those in Figure 26 constitute evidence which must be considered in connection with all other evidence bearing on the motions of the earth. The best proof for the earth's rotation is an experiment first performed by Foucault in Paris in 1851. This experiment when first performed was "front page news" the world over. The principle of the demonstration can be understood if we carry out a simple experiment with a heavy pendulum supported from the ceiling by a wire of such length that the pendulum bob just grazes the top of a table. A pin is attached to the lower end of the pendulum to trace a path in a layer of fine sand. The trace left by the swinging pendulum indicates its plane of swing. If, while the pendulum is swinging, the table is slowly turned, the pin will cut new traces in the sand to indicate the circular motion of the table top. The plane of swing of the pendulum thus serves as a means for indicating

the motion of the table top. For his experiment, Foucault used a wire two hundred feet long fixed to the dome of the Pantheon at Paris. When set in motion, his pendulum left a new mark in sand at each swing, and the veering was clockwise. This apparent veering clockwise is accounted for by the rotation of the floor (*counterclockwise*) under the plane of the vibrating pendulum. If the earth did not rotate, the stylus would have continued to trace the same groove on the sand. This experiment has been repeated many times. In the southern hemisphere the apparent deviation is counterclockwise or opposite to that in the northern hemisphere. At the poles the rotation would be a complete turn in twenty-four hours.

There are still other facts which cannot be adequately explained on any other basis except on the assumption that the earth rotates on its axis, making a complete turn once in twenty-four hours. The student will find references to some of these other proofs in the list of suggested readings. The direction of the rotation is from west to east; the speed of the rotation is greatest at the equator. This is obvious since a given point at the equator travels twenty-five thousand miles in twenty-four hours, a little more than a thousand miles per hour, while a point in the United States travels only about fifteen thousand miles, at the rate of about six hundred miles per hour in the same length of time. The rotation of the earth on its axis, once every twenty-four hours, produces the apparent revolution of all heavenly bodies around the earth in the same time. Hence the early notion of the hollow celestial sphere, with the heavenly bodies attached to its inner surface, rotating each day around an axis — the celestial sphere axis. It should be noted, however, that the celestial sphere appears to move in the direction opposite to the motion of the earth; the sun and the stars appear to rise in the east and to set in the west, because the earth rotates from west to east.

The Orbital Motion of the Earth

While rotating on its axis once every twenty-four hours, the earth at the same time is assumed to move around the sun in a path which is called its *orbit*. This motion is called the *orbital revolution* of the earth.

Actual observations do not show that the earth travels around the sun; they make it appear that the sun moves among the stars. If we observe the sun at noon, once a week for a year, we note that during the spring the sun climbs higher in the sky each day, until about the end of June, when it begins to descend toward the south, reaching, at about the end of September, the same noonday height that it had in the spring. As winter approaches, the sun moves to a lower and lower point until the end of December, when it begins to climb northward toward us again. In the spring, which is the end of the year of our observations, the sun reaches the same noonday height as it had when we started. This shifting of the sun's position marks the divisions of the year that we call the seasons.

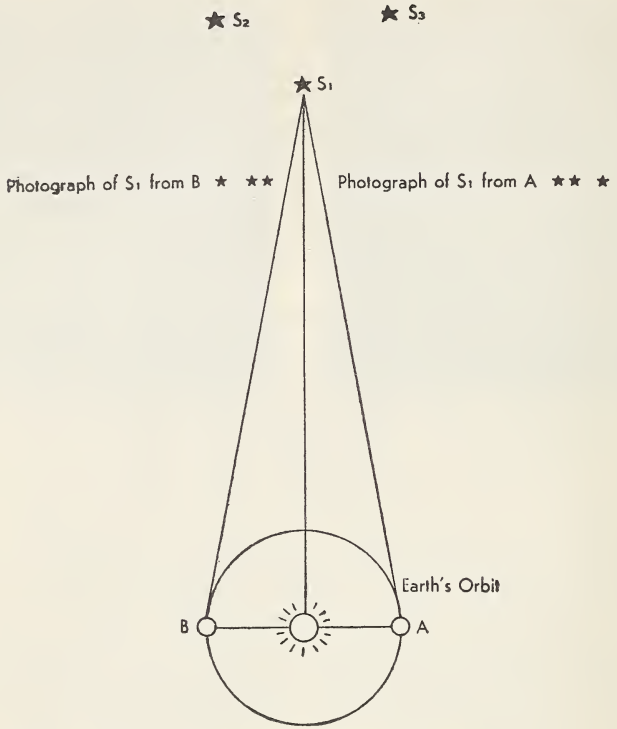


FIGURE 27. DETERMINING THE PARALLAX OF A STAR

Star S_1 is seen closer to S_2 or S_3 according as it is viewed from the opposite points A and B in the earth's orbit.

There are a number of ways to prove that this phenomenon is really caused by the revolution of the earth around the sun. The simplest is to select a particular bright star and note its position with reference to two of its neighbors which appear to be farther away in space. In order to record exact positions, we can take a photograph of this group and label each star by arbitrary symbols S_1, S_2, S_3. If the earth does not move around the sun, the star S_1 will remain always in the same direction from us and will appear always in the same position with reference to stars S_2 and S_3. But if the earth revolves, as is shown in Figure 27, the star S_1 will appear in January in different positions, with reference to the stars S_2 and S_3, from those in June. When the star S_1 is sighted from position A in January it appears closer to S_2 than S_3. Six months later, the earth is in position B, and when star S_1 is observed, it now appears closer to star S_3 than S_2

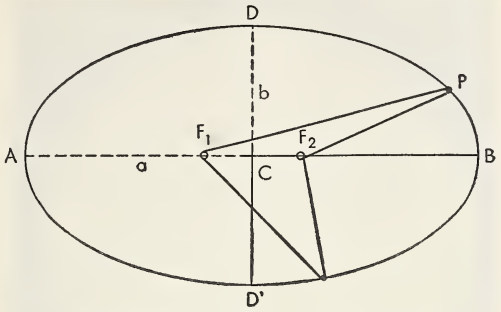


FIGURE 28. DIAGRAM OF AN ELLIPSE

Dotted line a *represents semi-major axis. The major axis is* 2a. *Dotted line* b *represents semi-minor axis. The minor axis is* 2b. *The sum of distance* $F_1P + PF_2 =$ *major axis or* AB *or* 2a.

This apparent shift of the near stars in relation to the faraway stars is called the *parallactic displacement.*

The Earth's Orbit. As stated above, the path which the earth follows in its revolution is called the *earth's orbit.* Since the earth returns annually to a given point, the form must have a circular shape. If we determined the distance to the sun at different times in the year, say every month, and if the distance from the center (sun) to the orbit (earth) remained the same throughout, then the orbit would be a perfect circle. But since the distances measured in January and June are found to differ by about 3 per cent, we arrive at the conclusion that the earth's orbit deviates slightly from a circle. The difference is so small that if one draws a circle so that the center is by 3 per cent closer to the right side than to the left, the eye cannot distinguish it from a perfect circle.

The form of the earth's orbit is an *ellipse.* An ellipse is a curve with two points within called *foci,* instead of one center as in the circle. The two positions are shown diagrammatically in Figure 28. The sum of the distances from any point on its circumference to the two foci is a constant. In Figure 28, the curve represents an ellipse of which the foci are F_1 and F_2. The midpoint C is called the *center.* The diameter AB which passes through the two foci is called the *major axis,* and the diameter DD' which is at right angles to AB is called the *minor axis.* If we represent half of the major axis by a and half of the distance between the two foci (line F_1C or F_2C) by c, then the ratio $c/a = e$ denotes the eccentricity of the ellipse. The less the eccentricity, the smaller the extent of deviation from a perfect circle; therefore, a perfect circle may be defined as an ellipse of zero eccentricity. The eccentricity of the earth's orbit is 0.016.

Since the earth's orbit is elliptical and not a perfect circle, with the sun

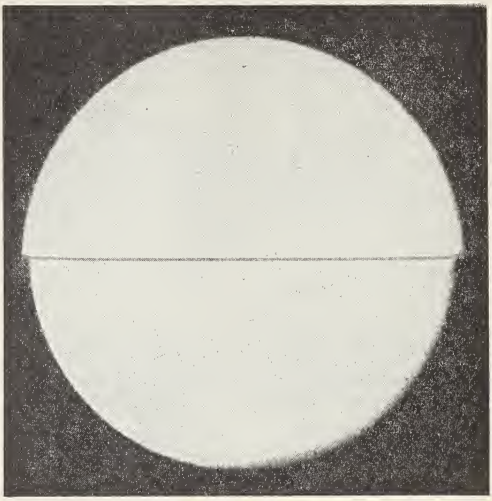


FIGURE 29. SUN'S APPARENT SIZE AT PERIHELION (TOP) AND AT APHELION (BOTTOM)
(*Courtesy of Mount Wilson Observatory*)

occupying one of the foci, it follows that there will be a position which will be closest to the sun. This position is known as the *perihelion.* A the point opposite the perihelion, the earth is farthest from the sun. This position is known as the *aphelion.* The line joining aphelion and perihelion, passing through the foci, is the major axis of the orbit. The positions are shown diagrammatically in Figure 34, page 75.

The greatest distance of the earth from the sun is 94,500,000 miles, o 152,200,000 kilometers, while the least distance is 91,500,000 miles, o 146,900,000 kilometers; the difference between perihelion and aphelion i in the neighborhood of 3,000,000 miles, or 5,000,000 kilometers. Th earth is found at the perihelion on January 3 or 4, and at the aphelion o July 3 or 4. The mean, or average, distance of the earth from the sun i 92,870,000 miles, or 149,450,000 kilometers. The sun, when photographe from the perihelion and aphelion, shows a difference in size. Figure 2 shows a comparison of the two photographs by superimposing one-half o the view taken from the perihelion on one-half of the view obtained fro the aphelion.

While considering these basic scientific facts and theories of the earth we should bear in mind that our present views are the product of sever thousand years of slow development. Though the present picture wa developed more systematically and with greater precision since the tim

of Copernicus, we should not forget that essentially correct ideas about the shape, size, and motions of the earth were discerned by some of the enlightened ancients. Eratosthenes' calculation of the circumference of the earth was about 250,000 stadia. Although we do not know the exact distance of a stadium, it is believed to be 517 feet. This would give 24,500 miles for the earth's circumference, a figure remarkably close to 24,800 miles as calculated by modern methods. The problem of the motions of the earth is more difficult, and yet both the rotation and the orbital motion were advanced as hypotheses in antiquity, though they did not gain wide and permanent acceptance since instruments for accurate observations were lacking. The earth's rotation on an axis was advanced by Heracleides, and the earth's revolution about the sun by Aristarchus. Unaided by a telescope, Hipparchus, one of the most brilliant of the ancient astronomers, discovered the eccentricity of the earth's orbit. Whether the earth moved in this orbit, as Aristarchus had proposed, or the sun, as everyone else believed, must have been an open question to Hipparchus for some time. If the earth revolved, he finally reasoned, there should be a parallactic displacement of the stars. Like a true scientist, he made observations to discover whether there was any such displacement, and failing to find any with the instruments he possessed, he came to the conclusion that the earth was at the center of a circle about which the sun revolved.

SUMMARY

1. The earth belongs to a family of heavenly bodies known as the solar system. It is one of the planets which revolve about a star known as the sun.
2. The appearance of ships when moving away from a stationary observer, the shadow of the earth on the moon during a lunar eclipse, and photographs of the earth's surface during stratosphere flights are proofs of the earth's curvature.
3. The circumference of the earth is 24,800 miles and the diameter 7917 miles.
4. The earth rotates about an axis which passes through two points called the poles.
5. Photographs of "star trails" at the equator and at the poles and the Foucault pendulum experiment are accepted as evidence of the earth's rotation.
6. The earth rotates from west to east with a velocity of about a thousand miles per hour at the equator.
7. The earth's rotation produces the apparent east-to-west motion of the sun and stars.
8. The earth revolves around the sun in an elliptical orbit, making a complete revolution in one year.
9. The shift of the near-by stars among the faraway stars as viewed from the earth at different times, called the parallactic displacement, is a proof of the earth's orbital motion.

10. The orbit of the earth is an ellipse; in an ellipse the sum of the two distances from any point on its circumference to two points within the curve, called foci, is a constant.
11. In the earth's orbit the sun occupies one of the foci; the other focus is an imaginary point in space.
12. The extent of the deviation of the earth's orbit from a perfect circle is about 3 per cent. The deviation is best given by the eccentricity, which is 0.016. Eccentricity is the ratio of the distance between the two foci to the length of the major axis.
13. Perihelion is the point on the earth's orbit closest to the sun, and aphelion the point most distant from the sun.

STUDY EXERCISES

1. Twelve of these technical terms are referred to in the definitive phrases below. Identify them by letter in the margin.

A. aphelion	E. eccentricity	I. orbital motion	M. rotation
B. accelerated motion	F. hydrosphere	J. perihelion	N. sphere
C. atmosphere	G. lithosphere	K. pi (π)	O. square
D. density	H. motion	L. radius	P. uniform motion

(1) The ratio of the mass of an object to its volume.
(2) A geometrical figure that has all points of its surface equidistant from the center.
(3) A change of position with respect to the observer.
(4) The gaseous envelope that surrounds the earth.
(5) Motion about an axis.
(6) The solid portion of the earth.
(7) Motion about a center.
(8) The ratio of the circumference to the diameter of a sphere.
(9) That portion of the earth which is water.
(10) Motion of a body that covers equal distances in equal intervals of time.
(11) The point in the earth's orbit closest to the sun.
(12) The extent of deviation from a perfect circle.

2. In the following, a list of observations is given. Place after each statement: *A* if the observation helps to prove that the earth is spherical in shape; *B* if it helps to prove that the earth rotates on its axis; *C* if it helps to prove that the earth has orbital motion; *X* if the observation proves none of these three statements.

Observation:

a) Smoke tends to go upwards..... ....
b) In traveling from Chicago to Florida, new stars come into view... ....
c) Freely falling bodies actually fall a little east of the point directly underneath the original point of support..... ....
d) At an altitude of a thousand feet the region visible to the observer is less than at two thousand feet..... ....
e) The sun always travels westwards..... ....

f) Fixed-camera photographs at the equator show star trails as straight lines, but at the poles the trails are circular.....

g) There are twelve new moons in a year.....

h) Photographs of distant stars taken in January show relative displacement when taken again in July.....

3. What evidence exists which indicates that the earth is not a perfect sphere?
4. Two cities, *A* and *B*, are situated 2075 miles apart. At each of these cities simultaneous observations are taken on a distant star which is directly overhead at *A*. The observer at *B* notes that his line of sight to the star makes an angle of 30° with his plumb line. Calculate from these data (using the method of Eratosthenes) the length of the circumference of the earth. Draw a diagram to illustrate your solution to this problem.
5. Mercury is a metal which is liquid at ordinary temperature. The mass of fifty cubic centimeters of mercury was found to be 680.6 grams. Calculate the density of mercury. How many times heavier is it than water?
6. Select the alternative that correctly completes each of these sentences:

   The circumference of the earth: (*a*) is 5 times its radius; (*b*) is the square of its radius; (*c*) is 3.14 times its diameter.

   The radius of the earth is: (*a*) greater at the poles; (*b*) greater at the equator; (*c*) the same at the poles and equator.
7. To account for the daily motion of the sun and stars, we can make three hypotheses: (*a*) there is a celestial sphere which holds the sun, moon, and stars, and which is turning; (*b*) there is an eastward rotation of the body upon which we live; (*c*) both the body upon which we live and the sphere move. Discuss briefly how each assumption fits the facts.

FOR FURTHER READING

1. Baker, Robert H., *An Introduction to Astronomy.* New York: D. Van Nostrand Co., 1947.

   A college textbook on astronomy. The chapter on the earth is well illustrated and gives a clear discussion of the motions of the earth.
2. Bartky, Walter, *Highlights of Astronomy.* Chicago: University of Chicago Press, 1935.

   An interesting presentation of astronomy written for the general student. The discussion of the earth as an astronomical body will be found in Chapter I.
3. Russell, Henry N., Raymond S. Dugan, and John Q. Stewart, *Astronomy.* Boston: Ginn and Company, 1945.

   A college textbook on astronomy. A detailed discussion of rotation and revolution of the earth will be found in Chapter 4.
4. Duncan, John Charles, *Astronomy.* 4th edition; New York: Harper and Brothers, 1946.

   A college textbook on astronomy. The discussion of the rotation and revolution of the earth will be found on pages 68–78.

5

The Concept of Time

IN CHAPTER 2 the unit of time was given as the second, without much elaboration as to the meaning of the term or the basis of this fundamental unit. There are many terms used in everyday speech expressing fundamental concepts without being defined: for example, *time*, *space*, *matter*, *force*. Having obtained our first look at the world, we are in a better position to consider the concept of time.

By a *concept* we mean the formulation of an idea in the simplest terms. If we can define the idea of time in the simplest possible terms, then it will become a fundamental or primary concept. The concept of matter is not very difficult to comprehend, for matter is objective; it can be seen; it can be held in one's hand. The concepts of motion and time, however, are difficult to formulate. We cannot get hold of them in our hands or see them with our eyes. But we can measure time and motion accurately and try to understand how they are related to more easily graspable matter.

The difficulties which arise when we try to understand time can be illustrated if we consider some phrases we use every day. We speak of "past," "present," "future"; of "losing time," or "not having enough time," or "having plenty of time." We find difficulty in explaining to ourselves just exactly what we "lose" or "do not have enough of." If we lose a dime or do not have enough oranges, we can easily explain our loss or insufficiency because we can point to a dime or to an orange. But we cannot feel, weigh or see time. After some reflection we may arrive at the conclusion that time is related to the events of our life. "I do not have enough time" means "I cannot do all the things I should like to do." Our memory of "yesterday" is related to "what took place yesterday," and therefore we begin to suspect that what we mean by time is the seeming length of intervals between events. If our day was full of doing things, time "flew" and the day appeared very short. If we had little to do yesterday and the day was dull, time "dragged" and the day seemed unusually long. Therefore we come to the conclusion that time as measured by watches and clocks is not the same as time measured by our minds. Time as ordinarily understood is *psychological time* measured by the events which come to our

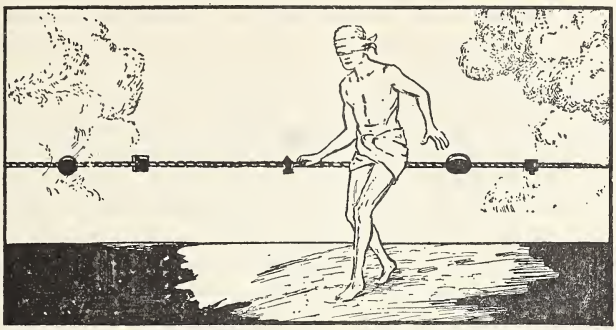


FIGURE 30. ILLUSTRATING PSYCHOLOGICAL TIME

nsciousness, and the concept is vague since it has no definite or absolute ındard. Psychological time may be illustrated by walking in the dark ıile holding a rope to which several objects are tied, as shown in Figure 30. ıe objects represent the events, and the rope is what is usually called ne; the rope between any two objects represents uneventful periods.

It is clear that irregular intervals as discerned by mental processes can-t be used as a *standard of time*. For such a purpose, it is necessary to oose an event that recurs at regular intervals. The event which rigorsly fulfills this condition is the apparent revolution of the celestial sphere, used by the rotation of the earth. This event has been used from re-ɔtest antiquity as a measure of time. An object like a star or the sun rectly overhead in the sky is chosen as a reference point. The interval tween the initial observation and the return of the heavenly object to e same point is called a day; hence the measurement of time is based on ɔtion — one complete rotation of the earth. To measure time accutely, it is necessary to have a system for locating a reference point in the y.

rcles of Reference on the Celestial Sphere

In the last chapter it was pointed out that the earth's rotation causes an parent daily rotation of the sun and stars, and that it early led to the tion of the celestial sphere with the heavenly bodies attached to its inner rface rotating each day around on an axis. Though we know that this tion is not correct, we will make use of it in order to develop a system of :ating the exact position of a heavenly body.

The celestial sphere is assumed to rotate on an axis which touches the :face at two points, the north and south celestial poles. Since the appart revolution of the celestial sphere is due to the earth's rotation, the lestial poles are the points where the earth's axis of rotation prolonged

in space would pierce the celestial sphere. Similarly, the plane of t earth's equator prolonged outward touches the celestial sphere at a cir called the *celestial equator*.

If we suspend from a string a small weight which tapers downward to point, the arrangement is called a *plumb line*. If we imagine the plum line to extend upward in the sky until it touches the celestial sphere, t point is called the *zenith*. The other end of the plumb line, extended the invisible part of the sphere directly opposite the zenith, reaches wh is called the *nadir*. If we draw a great circle around the celestial sphe midway between the zenith and t nadir — 90° from each of them — is called the *horizon*. In Figure 31, represents the zenith and *NESW* is t horizon. The term horizon in everyd speech means the imaginary bounda line where the sky meets the earth, a therefore depends on the landsca To distinguish between the two t latter is called the *visible horizon*.

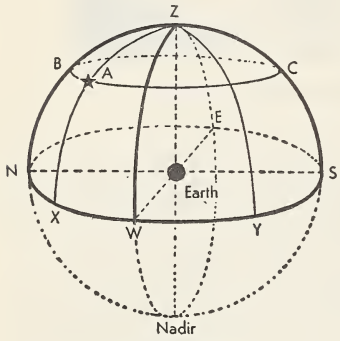


FIGURE 31
THE CELESTIAL SPHERE

In order to locate any point on t celestial sphere, vertical circles a drawn from the zenith at right ang to the horizon and through the nad We can draw as many circles as wish, so that any point in the sky c have one of these circles passing through it. In order to obtain a referen circle, we choose that great circle which passes through the celestial po known as the *meridian* circle. In Figure 31 the meridian is *NZS*. T points where the meridian intersects the horizon are the *north* and *so points*, while midway between them are the *east* and *west points*. To loca a heavenly body in the sky, we find the vertical circle passing through and then measure the number of degrees between it and the horizon. should be noted that we are measuring the arc of a circle and not a straig line, and therefore we must express it in degrees. In order to locate t star *A* in Figure 31, it is noted that it is situated on the vertical cir *ZX*, which of course can be prolonged to pass through nadir and then zenith. The arc *AX* in degrees expresses the angular elevation of star above the horizon, or the *altitude* of the star. The arc *AZ* is the zen distance of the star. In order to locate the star with reference to east a west, we start from the south point and proceed westward to the foot the vertical circle which passes through the star. This arc is the *azim* of the star. The meridian circle is the azimuth of star *A* (Figure 31, *SW*

dereal Time

Having obtained a method of locating a heavenly object accurately, we ın follow its apparent motion from day to day. Since the rotation of the lestial sphere is caused by the rotation of the earth, we take the interval quired for one complete rotation as a basis for the measurement of time. herefore, a particular "clock" star is selected and observed through a ansit telescope. This is a special type of telescope mounted on an axis st and west, so that it can follow the meridian of the place at which ıe telescope is mounted. The eyepiece is provided with special and licate apparatus to record exactly when the star crosses the thin line ross the field of view which designates the meridian. The transit of ıe selected "clock" star is observed and the time is recorded. The next ıssage of the star will occur when the earth has completed one rotation. he time of the second passage is recorded and this marks the completion one *sidereal* day. The sidereal or "star" day has a length of twenty- ree hours, fifty-six minutes, and four seconds of ordinary time. All dereal days are of equal length, but their use is restricted to astrono- ers, because most of our activities are regulated by the position of the ın in the sky and not by the position of the stars. The sidereal noon mes at different times of the day and night at different times of the year. or this reason the sun is used instead of a "clock" star. When the sun used as a reference body to measure the completion of one rotation of e earth, we have what is known as *solar time.*

lar Time

The method used for the observation of the transit of the sun is the me as used for "clock" stars. The interval between two successive ıssages of the center of the sun through the meridian is called a *true solar y.* The day is divided into twenty-four hours, each hour into sixty inutes, and each minute into sixty seconds. When a comparison is made tween the sidereal day and the solar day, it is found that the solar is out four minutes longer. The passage of the sun across the meridian ın be timed with a sidereal clock at noon today; tomorrow the sun will rive four minutes late at the same point according to the sidereal clock. ıis difference is due to the fact that while the earth is rotating it is also volving about the sun. The stars are so infinitely far away as compared th the sun that they appear in the same direction from our successive sitions. But the sun is nearer, and since, after one observation of the n, the earth advances in its orbit, the earth has to rotate a little farther r a second observation to see the sun passing through the meridian. ıis extra rotation takes nearly four minutes and accounts for the differ- ce in the length of a solar and a sidereal day.

The solar days vary slightly in length owing to the variation in the orbital

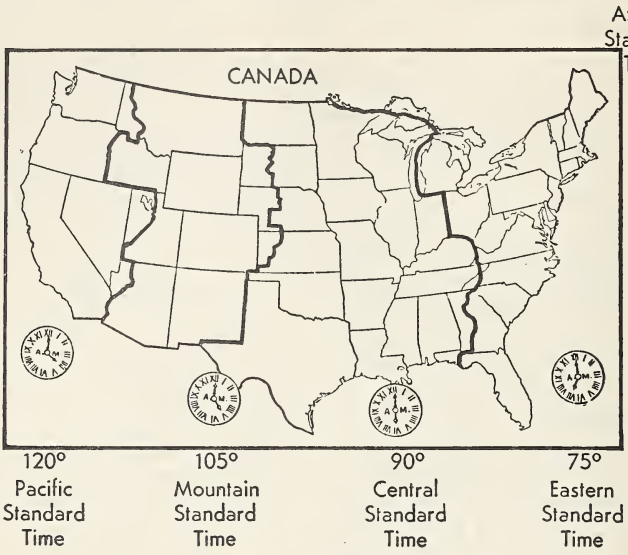


FIGURE 32. TIME ZONE MAP OF THE UNITED STATES
(*Zone boundaries are established and modified by the Interstate Commerce Commission*

speed of the earth. When the earth is at the perihelion, or closest to th sun, it travels faster, and when it is at the aphelion, it travels slower. I order to eliminate the situation of having the noon oscillate, it has bee found convenient to adopt a solar day, which is invariable, by making simple adjustment. The average of the lengths of all the solar days in th year is taken and called the *average* or *mean solar day*. Thus, the sun made to be at the meridian at mean noon; all mean solar days are equa One mean solar second is 1/86400 of a mean solar day; this is the funda mental unit of time. All ordinary clocks are constructed on the basis mean solar seconds.

It is quite obvious from the definition of mean solar time that what w call noon here is not noon two hundred miles west or east of us. The loc apparent noon changes as a person travels east or west. In order to avo the confusion which would result if each town and city had its cloc adjusted to the local apparent noon, it has become necessary to adopt system of keeping the same time in certain zone areas, each of which about a thousand miles in width. The time zones in the United State shown in Figure 32, are as follows:

(1) *Eastern*, which includes the region located east of a line running fr Cleveland to the western boundary of Florida;

(2) *Central*, which includes the region west of the Eastern line to the western boundaries of the Dakotas, Nebraska, Kansas, Oklahoma, and Texas;

(3) *Mountain*, which includes the regions extending from the Central line to the Rockies;

(4) *Pacific*, which includes the region west of the Rockies.

In addition to the four zones of standard time that are used in the nited States, most large metropolitan centers adopt daylight-saving time ıring the summer; this is one hour faster than standard time. Central ıylight-saving time, therefore, is the same as Eastern standard time. aylight-saving time was adopted throughout the United States as a artime measure.

For world-wide reckoning the following system is used. Vertical circles e drawn on the earth's sphere. In order to obtain a point of reference r measuring angular distances east or west, the vertical circle (merid-n), through Greenwich, England, is taken as zero, and the number of grees from this reference point is called the *longitude*. Thus, since there e three hundred and sixty degrees in twenty-four hours, it is obvious that r each fifteen degrees of longitude east or west of Greenwich there will be ıe hour's difference of time. Hence, each time zone in the United States presents fifteen degrees difference in longitude. The longitude of hicago is 87° W; this can be expressed also as 5.8 hrs W.

If a traveler starts from New York and proceeds west, he must set his ıtch back an hour for every fifteen degrees of longitude, or roughly one ousand miles, because the earth is moving eastward. If he takes a boat San Francisco and continues westward, he will apparently lose one day he goes around the earth. To simplify matters for travelers, by inter-ıtional agreement a change of date is made at the 180th meridian from reenwich. This line is in the Pacific Ocean, and a traveler going west-ard jumps one day when his ship crosses what is called the *International ate Line*. If a ship traveling westward arrives at the date line on the ening of June 10, it changes the date as it crosses the line to June 11. milarly, a ship traveling eastward and arriving at the date line on the ening of June 10 changes the date to June 9.

ngitude and Latitude

In the preceding section we defined longitude as angular distance east ıd west, using the meridian circle which passes through Greenwich as the ro point. Since we have also a means of expressing angular distance rth and south, we can locate with precision any position on the earth. ıe angular distance of a point on the surface of the earth north or south the equator of the earth is called its *latitude*. Since the pole star, olaris, at the equator is almost on the horizon, its altitude there is nearly ro; at the north pole, Polaris is nearly overhead and therefore has an al-

Parade

FIGURE 33. DETERMINATION OF THE ALTITUDE OF A STAR OR OF THE SUN BY MEANS OF A SEXTANT

titude of nearly 90°. Hence, for any city in the United States the altitu of Polaris is some angle a which can be measured directly by observati with instruments (meridian circle and sextant). The altitude of Pola then can serve to determine the latitude of the observer accurately.

Longitude is determined by taking the difference between the local tin and Greenwich time at the same moment. For example, suppose an o server in the United States finds that the time at his observatory is 5 hour 44 minutes, and 40 seconds *less* than the Greenwich time. This is equiv lent to longitude 86° 10′ west of Greenwich. This figure is obtained b multiplying the difference in time by fifteen degrees. Suppose, furthe that the angular distance of Polaris above the horizon as determined by t observer is 39°46′. This latitude together with the above-mentioned long tude corresponds to the location of Indianapolis, Indiana.

The Seasons

The alternation of the seasons — spring, summer, autumn, winter — familiar; its explanation is related to the motions of the earth and may b considered at this point because the seasons from the very beginning hav been used by men as points of demarcation in the reckoning of time.

The earth is assumed to turn about an imaginary axis which pass through the earth itself and meets the surface at the two poles. We ca

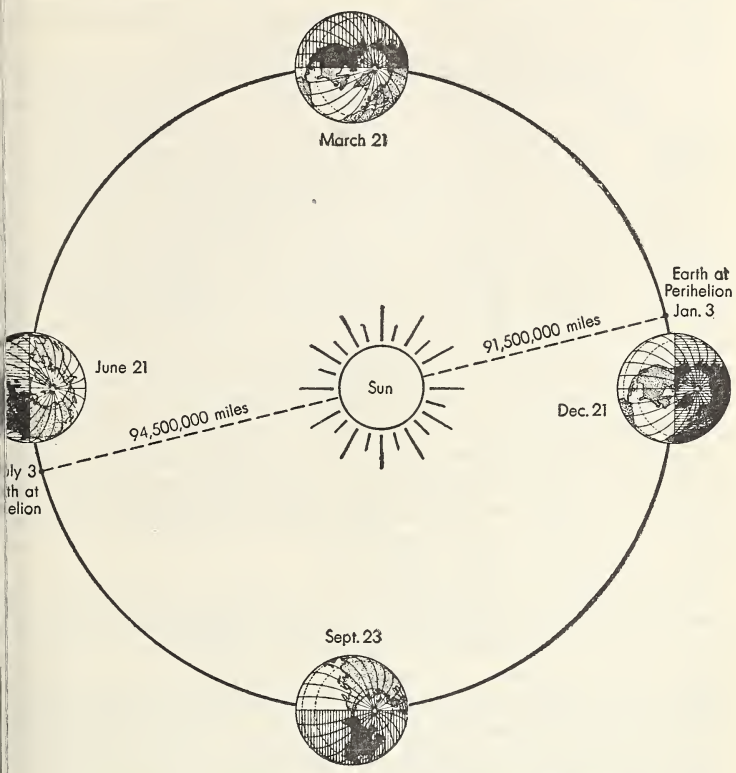


FIGURE 34. POSITION OF EARTH AT VARIOUS SEASONS

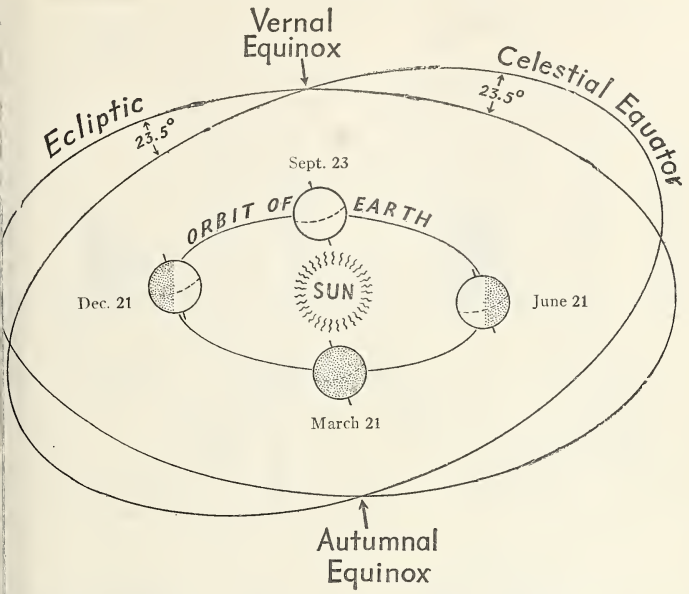
ce a small globe representing the earth at a distance from an electric
ıt bulb representing the sun. The axis on which the globe turns is so
anged that the light from the bulb strikes it in a direction perpendicular
ts axis. The plane containing the earth and the sun is called the *plane*
he ecliptic. Since our model earth's axis is perpendicular to the plane
ts orbit, it makes with the ecliptic an angle of 90°. If the real earth's
be were to rotate on its axis at this angle and to revolve slowly about
sun, we should have conditions over most of the earth vastly different
m what they are at present. At a latitude of 40–45°, which is about
lway between the equator and the north pole, the sun would rise always
he same place in the east, climb in the sky at 45° and set exactly twelve
ırs after sunrise; hence, day and night would be of equal length. The
nate would be an everlasting spring. At the pole the sun would always
at the horizon, never rising and never setting, but making a complete

round every twenty-four hours. Each place on earth would have appro
mately uniform year-round general weather conditions.

Now, suppose we tilt our model globe representing the earth 23.5°
that it makes with the ecliptic an angle of 66.5°. Then the variations
the seasons, the inequality of day and night in our latitudes, can be e
plained. If we incline the north pole of our model toward the sun,
will obtain an idea of the position of the earth during the summer at o
latitude. The day is almost fifteen hours long. The north pole is co
tinuously illuminated as the earth rotates; the illuminated portion is
circle of 23.5° from the pole, called the *Arctic Circle*. At the southe
hemisphere, which is tilted away from the sun, the reverse conditions exi
The days are short; at about 40°–45° south there is daylight for abo
nine hours. The south pole and the territory of a circle 23.5° from it,
enveloped in a long night. If we incline the north pole of our model aw
from the sun, to the same degree, it is obvious that we will have exact
the opposite conditions in each hemisphere from those described above
summer in the southern hemisphere and winter in the northern hemisphe
If we tilt the model to the right or to the left to the same degree (23.5
as before, we obtain the approximate positions of the earth in the spri
and fall. With this rough illustration in mind, the alternation of seas
can be considered in greater detail.

Refer to Figure 35. As previously noted, the plane of the ecliptic is t
plane determined by the sun and the earth. Suppose this plane is p
jected outward until it intersects the celestial sphere, it will form a gr
circle called the *ecliptic*. A little reflection will show that this circle
related to the earth's orbit, since this circle marks the apparent path
the sun among the stars in the course of a year. It will be also recall
from previous discussion that the celestial equator is the circle which t
earth's equator marks on the celestial when projected outward from t
earth until it intersects the celestial sphere. The ecliptic intersects t
celestial equator in two points (situated opposite to each other) at
angle of 23.5°; these points are called the *equinoxes*. These are the poi
where the sun apparently crosses the equator, moving northward on
about March 21 (the *vernal equinox*) and southward on or about Septem
23 (the *autumnal equinox*). Midway between the equinoxes — that
ninety degrees from each other on the ecliptic — are points called *sum*
and *winter solstices*. These two points represent the two positions of
treme declination of the north pole toward and away from the sun.

Consider the position of the earth on the vernal equinox, referring
Figures 35 and 36. The axis of the earth is perpendicular to the line
light between the sun and the earth. The sun is at the horizon at b
north and south poles; at the north pole it is rising after the long Arc
night, and at the south pole it is about to set after a long Antarctic d
Since the axis of the earth is perpendicular to the plane of the eclip



IGURE 35. RELATION OF VERNAL AND AUTUMNAL EQUINOXES TO THE ECLIPTIC AND CELESTIAL EQUATOR

hence is not turned toward or away from the sun, night and day are l everywhere on earth. The position of the sun at noon as measured he meridian altitude varies from 0° at the poles to 90° at the equator. ıe United States at about 42° north (New York or Chicago), the meri- altitude of the sun is 48°, as shown diagrammatically in Figure 36. eginning with the vernal equinox, the length of the day in the northern isphere increases while in the southern hemisphere it decreases; as the th of the day increases, the meridian altitude of the sun also rises; in r words, the sun rises to a higher and higher position at noon. Since rays become more perpendicular and the heat is received for longer ods, the weather is generally warmer. When the summer solstice es on June 21, the north pole (see Figure 34) is turned toward the sun; length of day in the northern hemisphere at about 40°–45° latitude is en hours, while in the southern hemisphere at a corresponding latitude length is nine hours — and the season is winter. The sun in the hern hemisphere climbs at noon to an altitude of 23.5° at the pole and ° at about 42°. The amount of heat, for reasons already pointed out, proceeded to the point where the loss by radiation during the nights mes smaller than that received by day, and so there is an accumulation

FIGURE 36. APPARENT PATH OF THE SUN THROUGH THE SKY IN THE UNITED STATES AT LATITUDE OF 42° ON MARCH 21, JUNE 21, SEPTEMBER 23, AND DECEMBER 21

eat from day to day which causes a rise in temperature familiar in the spells of July and August.

eginning with the summer solstice the noonday altitude of the sun eases, and the length of day decreases, until at the autumnal equinox meridian altitude is the same as at the vernal equinox; as shown in ıre 36 for a latitude of 42° the noonday altitude is 48°. The conditions eptember 23 are the same as those described above for March 21. In northern hemisphere, the advance of fall is marked by decrease in the th of days and increase in the length of nights. The sun moves to a r and lower point at noon. Since the length of daylight has decreased the rays of sun strike at an angle, the amount of heat gained becomes ller than the amount lost by radiation, and hence the weather becomes er in the northern hemisphere while the reverse holds true in the hern hemisphere. On December 21 the conditions are the reverse of e described for June 21. In the United States the length of day –45° latitude) is about nine hours; the sun climbs only about 24° at ı (see Figure 36). Above a latitude of 66.5° north there is no daylight ll, and south of 66.5° there is no night at all. After the winter solstice, n the northern hemisphere is inclined away from the sun, the revolu- of the earth in its orbit brings it on March 21 to the position of the ıal equinox from which we set out on our seasonal journey. The con- ons in the equatorial regions do not change appreciably during the . Strictly speaking, there are no seasons at the equator; and the th of day and night are about equal throughout the year.

should be noted that not only are the seasons in the northern and the hern hemispheres reversed, but there is also a difference due to the tion of the earth in its orbit during winter and summer. In the hern hemisphere summer occurs in December and January, and it is er than the northern summer because at this time the earth is at the helion and consequently receives more heat. The amount of ocean so greater, and since large bodies of water gain and lose heat slowly, reduces the temperature difference between seasons. Similarly, the er in the southern hemisphere is colder than in the northern, since earth is at the aphelion in June. This causes a slight variation in the th of the season in the two hemispheres. In the northern hemisphere, mer is 4.5 days longer than winter, and spring is 3.8 days longer than er; autumn is about one day longer than winter. The reverse is true ıe southern hemisphere.

Calendar

he reckoning of time over long intervals is made in terms of the year. erally the year may be defined as the time required for the earth to plete one revolution in its orbit about the sun. More precisely, it is time included between two successive arrivals of the sun at the vernal

equinox. This is called the *tropical year*, and its length is 365.2422 m solar days.

The subdivision of the year into months and weeks and the syste keeping account of the years was developed early and was based on motion of the moon. The phases of the moon have always been obj of great interest. Since the moon completes its revolution (with refere to the sun) in 29.5 days, there are 12.4 lunations, or intervals between moons, in a year ($12.4 \times 29.5 = 366$ days). It was this which gave to the division of the year into twelve months.

The duration of the months has varied in history. In Egypt and Gr the month had thirty days. The Romans had a very cumbersome ca dar, regulated by the various pontiffs, and naturally this led to great fusion. Julius Caesar, in 46 B.C., with the advice of the Alexand astronomer Sosigenes, established the basis of the present form of calendar. The length of the year was fixed at 365 days with every fo or leap year to have 366 days. The beginning of the year was cha from March to January. The distribution of the days in the months made so that the odd-numbered months had thirty-one days and the e numbered months had thirty days, except for the second month (Fe ary), which was allotted but twenty-nine. The name of the fifth m (in the old calendar), was changed by Caesar from Quintilis to July; l his successor, Augustus, removed one day from the second month added it to the sixth (Sixtilis), which he renamed August after himse

The normal Roman year devised by Caesar had 365 days, and e fourth year 366 days. This implied that the tropical year contains 36 days, while in reality it has 365.2422, or 0.008 of a day shorter. As sult, with the passage of one thousand years the Julian calendar ha error of eight days. In 1582 the date of the vernal equinox had sh from March 21 to March 11. In that year, Pope Gregory changed Oct 5 to October 15, dropping ten days. To prevent further displacem it was decreed that the rule of adding one extra day every fourth should be followed except in the case of those century years w number is not divisible by 400. Thus, A.D. 1700, 1800, and 1900 not leap years while 2000 will be a leap year. The Gregorian cale is used by practically all the Christian nations. The Jewish and Mo medan calendars are based on the lunar month.

The week is a period of seven days and has no reference to cel motions. It was not used by the Greeks or Romans, but originat Eastern countries, probably through the assignment of certain da the celestial bodies then known as planets as shown in Table 6.

The day as previously defined is 1/365.2422 of the interval require two successive passages of the sun through the vernal equinox.

Reform of the Calendar. Improvements of the present calendar been proposed from time to time. The reform most often proposed

TABLE 6. DERIVATION OF NAMES OF WEEK DAYS

Day	Latin Name	Saxon Name	English Name
1	Dies Saturni	Seterne's day	Saturday
2	Dies Solis	Sun's day	Sunday
3	Dies Lunae	Moon's day	Monday
4	Dies Martis	Tiw's day	Tuesday
5	Dies Mercurii	Woden's day	Wednesday
6	Dies Jovis	Thor's day	Thursday
7	Dies Veneris	Frigg's day	Friday

one month and thus have thirteen months of twenty-eight days each, New Year's Day not assigned to any month. The leap-year rule ld have to be retained, and the extra day assigned between June 28 and 1. In the proposed reform, all days and dates are fixed; the first of y month would fall on Sunday, and the last Saturday in a month ld be the twenty-eighth. All months would be alike, and no new cal- ır would be required for each year. Changes of customs and practices, ever, are slow, and further calendar reforms may not take place for y years.

SUMMARY

Time, like matter, energy, and space, is a fundamental concept, or an idea defined in its simplest terms. Such concepts are difficult to define, though easy to measure.

Time as ordinarily understood is psychological time, measured by the events which come to our consciousness.

The measurement of time as used in science is based on one complete rotation of the earth on its own axis and also about the sun.

The measurement of time involves the accurate location of a celestial body. Circles of reference on a hypothetical sphere are used in one system of location.

The point directly overhead, as shown by a plumb line, is called the *zenith*. The great circle which passes through the celestial poles and the zenith is the *meridian*.

The altitude of a star is its angular elevation above the horizon. The angular distance east or west measured from the south point on the horizon is the *azimuth*.

The interval required from one complete rotation of the earth with a star as reference point is a *sidereal day*.

The interval required for one complete rotation of the earth with the center of the sun as reference point is a *solar day*.

All sidereal days are equal; solar days vary slightly. The sidereal day is about four minutes shorter than the solar day.

A *mean solar day* is the average of all the solar days.

The standard unit of time is 1/86400 of a mean solar day and is called one *second*.

12. Owing to the rotation of the earth, noon varies over various places. Th are four time zones in the United States; each covers about a thousand m in width and differs by one hour.
13. *Latitude* is the angular distance north and south of the equator on the s face of the earth. *Longitude* is the angular distance east and west of Gre wich, England.
14. The earth's axis is not perpendicular to the plane of its orbit, but is incline an angle of 23.5°. This is the cause of seasonal variations.
15. The *ecliptic* is a great circle formed on the celestial sphere by the outw projection of the plane made by the earth and the sun. The two point which the ecliptic intersects the celestial equator are the *equinoxes*. *solstices* are the two points in the ecliptic where the sun is farthest from equator.
16. The *tropical year* is the time included between two successive arrivals of sun at the vernal equinox.
17. The calendar is the method of reckoning time over long intervals. Th have been several reforms of the calendar now used.

STUDY EXERCISES

1. To us it appears that the sun and the whole celestial sphere revolve about earth. Up to three centuries ago this was the accepted view. What f made the change necessary?
2. Give a concise definition of each of these terms:

longitude	azimuth of a star	vernal equinox
latitude	tropical year	winter solstice
aphelion	sidereal day	International Date Line
perihelion	solar day	Standard Time Zone
zenith	mean solar day	lithosphere
nadir	meridian	uniform motion
altitude of a star		

3. Make a drawing of the celestial sphere. On the basis of your drawing plain: zenith, nadir, altitude of a star, horizon, meridian, ecliptic, cele equator.
4. Show by a diagram the earth at vernal and autumnal equinox, and at s mer and winter solstice. Show that the southern hemisphere has sum weather during December; that on June 21 the sun shines twenty-four h at the north pole; that the sun shines twenty-four hours at the south pol December 21; and that the equatorial regions have no seasons.
5. Consulting a map, determine the longitude and latitude of the following ternational Falls, Minnesota; San Francisco, California; San Antonio, Te Portland, Maine; and Miami, Florida.
6. (*a*) A boat starts from Liverpool for New York and covers the distan three thousand miles at an average speed of eighteen miles per hour. boat started at midnight of October 1. Give the date and the Eas Standard Time that it will arrive in New York, assuming, of course, it maintains its average speed throughout.

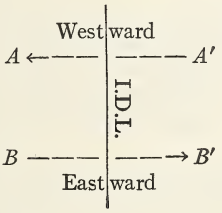
5) The speed of boats is usually expressed in *knots*, or nautical miles per hour. The *nautical mile* is defined as one-sixtieth of one degree or one minute of arc on the earth's surface at the equator. Calculate the number of feet in one knot. Express your answer also in kilometers.

Write a short paragraph explaining the main purposes and advantages of the proposed new type of calendar containing thirteen months.

Explain the meaning of the term *time* as commonly used, as measured by clocks, and as used in science.

Assume that you wish to measure longitude. What instruments do you require, and what methods would you use?

Consider two ships crossing the International Date Line. In position A the time is 9:00 A.M. Tuesday. What time is it at A', at B', and at B?



A is going westward
B is going eastward

FOR FURTHER READING

BAKER, ROBERT H., *An Introduction to Astronomy.* New York: D. Van Nostrand Co., 1947.

BARTKY, W., *Highlights of Astronomy.*
A discussion of time and its measurement will be found on pages 26–56. The topic of seasons is discussed on pages 18–25.

DUNCAN, J. C., *Astronomy.*
Circles of reference for locating position will be found in Chapter 1. The discussion of time, calendar, and seasons will be found on pages 97–122.

RUSSELL, H. N., R. S. DUGAN, and J. Q. STEWART, *Astronomy.*
The discussion of seasons will be found on pages 147–150. The various systems for locating the position of heavenly bodies are given in Chapter 1.

6

A Closer Look at the Earth

AN ATTEMPT WAS MADE in Chapter 4 to gain a certain familiarity with earth. That body was pictured as a spherical ball bulging in the m and pushed in at top and bottom, and spinning about its axis as it rev around the sun. In the present chapter a closer examination will be m in order to begin the study of the most obvious changes that occur o face of the earth.

Even a casual look discloses that changes are constantly occurri both the living and the lifeless things upon the earth. The living wo plants, relatively stationary, and of animals, restlessly moving abo dependent for life upon changes within and without; living bodie born from seeds or eggs, grow, reproduce, die, and then undergo d The plants are rooted to the soil and obtain their food from it and fro air. The animals live either on plants or on other animals which su on plants. Man is no exception. For thousands of years the present of man has tilled the soil to obtain food. Generations of men succe one another without noticeable intellectual progress, their functions mainly to toil, reproduce their species, and die. Only a few genera of men in some parts of the globe have succeeded in recording a few of history. Thus man, like other animals, is dependent on the soil soil alone will not suffice even for plants to grow. It is common know that without the atmospheric changes that result in rain, the green soon becomes a desert, parched and baked by the sun. The most n able changes in the atmosphere are variations of temperature, pre and moisture; these variations are usually denoted by the term *weat*

The Atmosphere

The geographic globe by which the earth usually is represented g poor picture of the face of the earth. It does not show the gaseou velope, the *atmosphere*, which surrounds the earth. The atmosphere of the three divisions of the earth; the other two are the *hydrospher* the *lithosphere*. The hydrosphere, or "water-envelope," covers 71 per cent (143 million square miles) of the earth's surface in the fo

eans, seas, lakes, and rivers. The hydrosphere fills the depressions of e solid sphere; the depth of these depressions reaches in some points six iles. The lithosphere, or "stone-sphere," comprises the solid portion the earth. Those parts which rise above the sea are known as conti- nts or continental masses. The surface of the lithosphere is not smooth :e that of the hydrosphere, but is marked with hills, ridges, and moun- in ranges. The highest peak is nearly six miles and hence the maximum fference in the elevation of the earth's surface is about twelve miles.

The mass and some of the general properties of the components of the hosphere and hydrosphere are not difficult to demonstrate. We are ways conscious of the mass of rocks and water. It is less obvious but less possible to demonstrate that air has mass. A deflated inner tube)m a tire is weighed, then inflated with air and weighed again; the in- ease in weight shows that air and — by implication — all gases which nnot be seen, have mass. Other properties of the atmosphere are nsive. It is odorless, tasteless, and colorless; it is not usually felt unless e moves rapidly through it. Like all gases, it can be compressed and panded.

The term air is used to desig- te the mixture of substances of nich the atmosphere is composed. r, like all mixtures, does not have e same composition throughout. is common knowledge that air certain regions is more dry, or ntains less moisture, than in ners. The composition of air at l level and at great altitudes ries. Table 7 gives the constitu- ts of air, and Figure 37 shows grammatically its composition. spection of the table shows that o gases, nitrogen and oxygen, ke up the bulk of air. Nitro- n and oxygen are elementary

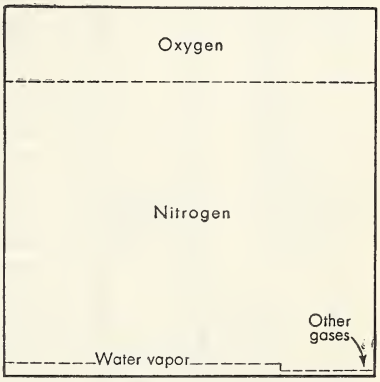


FIGURE 37. COMPOSITION OF THE EARTH'S ATMOSPHERE

TABLE 7. COMPOSITION OF AIR

nstituent	Density	Per cent by volume at sea level	Per cent by volume at elevation of ten miles
rogen	1.250	77.14	79.86
ygen	1.429	20.69	19.35
re gases	.....	0.93	0.07
rbon dioxide	1.977	0.03	0.01
ter *	.....	1.20	0.01
st particles †	.....		

Varies up to 5 per cent. † Variable.

substances or elements. The name element is applied to pure substance which cannot be broken down by ordinary methods, such as heating, int other kinds of substances. The rare gases need not be considered in th present discussion. Carbon dioxide results from combination of th elements carbon and oxygen; it is produced in the respiration of anima and combustion of fuels. It is constantly being removed from air by plan and utilized as food. Water occurs in air, either in the form of vapor as clouds or fog in minute droplets or even minute crystals of ice. Th amount of water varies at or near the surface of the earth from sma amounts in hot arid regions to about 5 per cent in the very moist region Dust is an impurity carried by the wind. The number of dust particl is usually high in industrial centers and may reach two hundred thousan or more per cubic centimeter of air.

Of the gaseous components of the atmosphere, oxygen and carbo dioxide are directly used in the vital processes of animals and plants. Th chief function of nitrogen is to dilute oxygen. Carbon dioxide is utilize by plants as food. Dust particles fu nish nuclei for the condensation of wat vapor and, by scattering light, help to gi the sky its characteristic appearance.

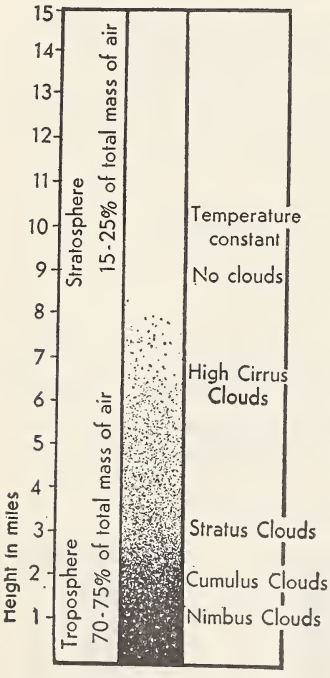


FIGURE 38. THE TROPOSPHERE AND THE STRATOSPHERE

The mass of the atmosphere in a give volume varies as one climbs a mounta or flies upwards in an airplane; the a becomes gradually "thinner" as t altitude increases. The common expe ence of difficulty in breathing at hi altitudes shows that the amount of ox gen is less than at the surface of t earth. About one-half of the total ma of the atmosphere lies within the fi 3.5 miles. Above an altitude of ten eleven miles, only about 15 per cent the total mass of air exists. The low region is known as the *troposphere* a the upper region as the *stratosphe* The troposphere extends about elev miles high at the equator and four mi at the poles. It is a region of continuo circulation of the gaseous componen and is characterized by clouds, fo rains, lightning, wind, air curren and fluctuations in temperature. T stratosphere begins above an altitu averaging about seven miles. In c

ast to the troposphere, it is a region of eternal quiet, with a constant mperature (about −55° Fahrenheit in the latitude of Chicago), and free m dust, storms, and clouds. The earlier knowledge of the stratosphere s obtained by means of kites and sounding balloons carrying automatic cording instruments. Since 1931 stratosphere flights have been made the use of special balloons. The first, by Auguste Piccard, reached a ight of 52,000 feet. The highest altitude so far attained is 72,395 feet, Stevens and Anderson (United States Army and National Geographic ciety, November 11, 1935). Figure 38 shows the extent of troposphere d stratosphere.

The stratosphere becomes thinner and thinner toward the outer space til it merges with traces of gases that exist in the spaces between the nets. One method used in estimating the height of the atmosphere is servation of meteors, or "shooting stars." Meteors which enter the rth's atmosphere are solid matter ordinarily varying in size from that a pinhead to that of a walnut. Since they move with very high velocis, they create tremendous friction as soon as they enter the region in ich air is present. This causes a rise in temperature until they become andescent, burning as they fall toward the earth and leaving a luminous il. Meteors usually become vaporized before they reach the tropohere, and very rarely fall to the ground. If the same meteor can be n or photographed by two observers stationed a few miles apart, it is ssible to determine the actual height of the meteor by triangulation. eteors usually appear at heights of not over one hundred miles, but some teors have been observed at heights close to two hundred miles. This licates that even at these heights some air exists. Observations of the rora borealis show that the rare gas helium exists up to a height of five ndred miles above the surface of the earth.

It should be realized, however, that at heights much above twenty-five les the gases of the atmosphere are in an extremely rarefied state. Even altitudes of five miles the air is so rare that the lungs cannot absorb a fficient quantity of oxygen to support human life. For this reason all ators seeking high altitudes are provided with tanks containing comssed oxygen for respiration. For the same reason airplane engines ist be equipped with compressors (superchargers) to compress the air ore it enters the engine intake.

The region above the stratosphere, at an elevation of about twelve to een miles above the earth, called the ionosphere, contains a large amount ozone, or active oxygen gas, and above this, at an elevation of about y miles, is the Kennelly-Heaviside layer, named after the scientists who st hypothesized the existence of such a region. The gases in this gion have a very high electrical conductivity and are of great importance radio broadcasting. The radio waves from the broadcasting stations

travel in all directions, and if this highly conductive layer were not prese they would travel out into space. But the presence of electrically charge gaseous particles in this layer causes the radio waves to be reflected bac to the earth and by thus confining them makes long-distance receptio possible. The complete breakdown of ove seas radio communication for two or three da periods has been associated with sunspot a tivity, at which time it is believed that gaps appear in the Kennelly-Heaviside layer and the radio waves pass out into space.

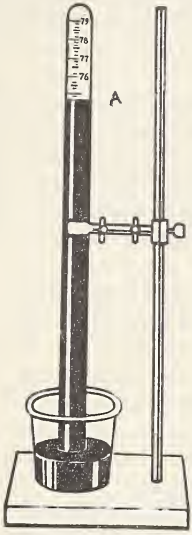


FIGURE 39. MERCURIAL BAROMETER (*Experimental type*)

Atmospheric Pressure

If a person dives to the bottom of a swimming pool ten feet deep, he feels *pressure* because of the mass of the water above. In the same manner the air of the atmosphere exerts pressure upon the objects on the earth because of its mass. This pressure, however, is seldom noticed and methods for its measurement were not developed until the seventeenth century. Prior to this time the operation of water pumps was explained on the theory that "nature abhorred a vacuum." Air was drawn out of the tube by the pump, and since nature had a "*horror vacui*," it made the water rush in and fill the void. When in 1640 a deep well was dug and no pump could be found that would lift the water higher than thirty-two feet, it occurred to Galileo that it was curious that nature did not detest vacuum above thirty-two feet. He concluded that nature's horror of vacuum was a force that could be measured. Galileo had previously proved that air has

FIGURE 40
MERCURIAL BAROMETE
(*Commercial type. Courte Chicago Apparatus Co.*)

eight, and Torricelli, Galileo's pupil, used a column of mercury instead a column of water to balance the weight of air and so established nnection between the weight of air and nature's horror of a vacuum.

An instrument for the measurement of the weight which a column of r exerts, in other words, the pressure of the atmosphere, is known as a *rometer*. The instrument shown in Figure 39 is similar to that con-ructed by Torricelli. It consists of a glass tube nearly a yard long, osed at one end and filled with mercury. If the open end is closed with e thumb and the tube is inverted in an open dish of mercury, and then e thumb removed, the mercury in the tube will descend to a height arked in Figure 39 by *A*. At sea level the height of the column is venty-six centimeters. This indicates that the pressure of air on the ercury in the open dish is enough to balance the mass of mercury in the lumn. In other words, there are two columns: one of mercury and one air. The column of mercury is seventy-six centimeters high; the column air extends from the surface of the dish to the outermost region of the mosphere — a point in space where air ceases to be present. Since the lumn of air balances the column of mercury, it follows that if the two lumns have the same diameter their masses are equal. To obtain a

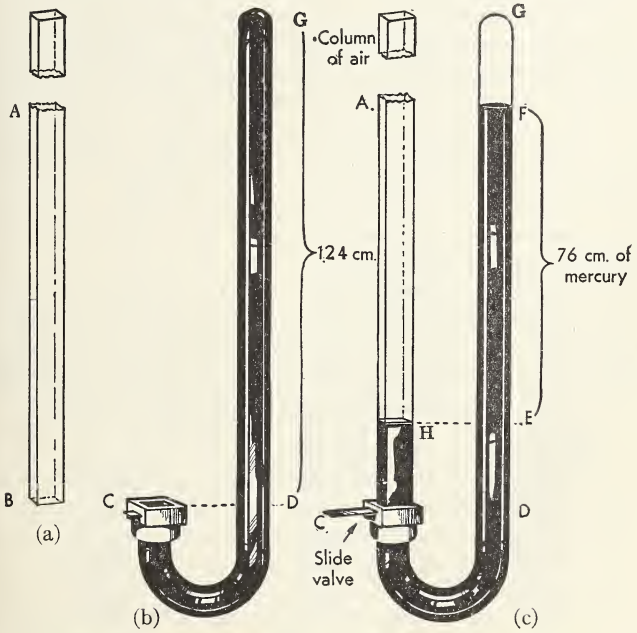


FIGURE 41. DEMONSTRATION OF ATMOSPHERIC PRESSURE

measure of this mass, let us consider a column of air one centimeter squar and extending upward to the topmost part of the atmosphere. Figure 41(a represents such a tube. If we obtain a tube one centimeter square an one meter in length, its upper part *A* can be imagined to extend upward t the limits of the atmosphere because the pressure exerted at *B* would b that owing not only to mass of air between *A* and *B*, but also to a colum of air of the same cross-section extending above *A* to the topmost part the atmosphere. The mass of this column of air is equal to 1033.6 g. Th value is obtained as follows: tube *CDG* as shown in Figure 41(b) is close at one end and at the lower end *C* it has an opening with a square coll fitted with a sliding piece of metal. The tube is filled at the level of t sea with mercury and the sliding stopper is pushed in. Now the tu shown in Figure 41(a) is placed on top of the collar at point *C* and fitted as to make an airtight joint. This combination produces a U-tube. T slide at *C* is pulled out; the mercury falls down to *F* as shown in Figure 41(and then stops, since the column of air on the other side of the U-tu counterbalances the column of mercury *EF*. The height of the mercu column *EF* is seventy-six centimeters or nearly thirty inches. The ma of this column of mercury is 76 cc × 13.6 g per cubic centimeter = 1033.6 Therefore, the column of air from point *H* extending to the topmost pa of the atmosphere has a mass of 1033.6 g per square centimeter. Cons quently, it exerts the amount of pressure which is called the atmosphe pressure at sea level, commonly expressed simply as 76 cm (760 mm), 29.92 inches. In other words, the pressure exerted by the atmosphere equal to that of a column of mercury 76 cm high. This atmosphe pressure may be expressed in terms of a column of water 33.9 feet hig or as 14.66 pounds per square inch, or 1013.2 millibars.[1] It is usua expressed in centimeters or inches of mercury, but all weather maps u millibars. The relation between centimeters and inches of mercury a millibars is shown in Table 8.

Since the atmospheric pressure is the weight of a column of air abov unit area in a particular region to the topmost part of the atmosphere, follows that there should be a variation of atmospheric pressure at s level and at the top of a mountain, for example, at Pike's Peak. Whe

Table 8. Units for Measuring Atmospheric Pressure

Centimeters of Mercury	Inches of Mercury	Millibars
76.00	29.92	1,013.2
74.93	29.50	999.0
73.66	29.00	982.1
72.39	28.50	965.1
71.12	28.00	948.2
68.58	27.00	914.3

[1] The *bar* is a common unit for measuring atmospheric pressure equal to 1,000,000 dynes square centimeter. One atmosphere is 1.0132 bars.

Table 9. Relation Between Barometric Pressure and Altitude

Altitude Feet	Barometric Pressure Inches	Centimeters	Millibars
0 — sea level	29.92	76.0	1013
1000	28.86	73.2	980
2000	27.82	70.7	945
3000	26.81	68.0	910
4000	25.84	65.7	875
5000	24.89	63.5	845
10,000	20.58	52.5	700
15,000	16.88	43.0	570
20,000	13.78	35.1	470
24,000	11.80	30.0	400

ırometer is carried to the top of such a peak, the column falls, since the ass of air from the peak to the topmost part of the atmosphere is less an in a corresponding column from sea level. Table 9 lists barometric essures at different altitudes. From the table it is clear that for each ch of decrease in pressure of mercury in the lower levels of the atmosphere e elevation increases approximately one thousand feet. A barometer ıich is calibrated to read altitude directly and which is extensively used airplanes is called an *altimeter*. Since oxygen comprises approximately e-fifth of the atmosphere at sea level, it follows that the normal person sorbs oxygen at a pressure of one-fifth of one thousand millibars or two ındred millibars. Inspection of the table shows that the pressure of the mosphere at 10,000 feet is 700 millibars, and therefore the oxygen pres- re is $700/5 = 140$ millibars. At 24,000 feet the oxygen pressure is $0/5 = 80$. At this oxygen pressure a person becomes unconscious. The ygen pressure may be increased by adding pure oxygen to the air, but en with an atmosphere of pure oxygen in an open cockpit of a plane a rson becomes unconscious at an altitude of about 45,000 feet. The fficulty is overcome by increasing the air pressure in a sealed cabin plane. The mercury barometer is not easily transported, and therefore the eroid barometer (Figure 42) is more commonly used. This consists of a ıall corrugated metal box, partially exhausted of air and hermetically ıled. As pressure on the box varies, the top moves in or out, and this ɔtion is multiplied by a system of levers and transmitted to a pointer ıich moves over a graduated scale. In the recording barometer, or *rograph* (Figure 43), the pointer is replaced by a long arm provided with pen. The pen rests on a piece of ruled paper wrapped on a drum re- lved by clockwork. In this manner, a graph of the various barometric essures through the day or week is obtained.

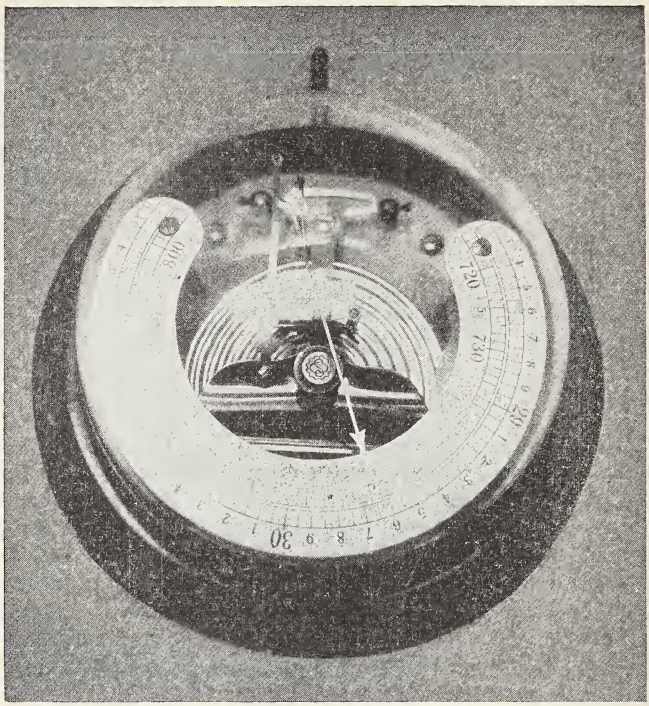


FIGURE 42. ANEROID BAROMETER (SHOWING MECHANISM)
(*Courtesy Chicago Apparatus Company*)

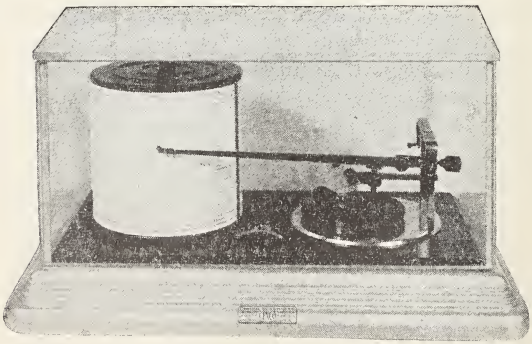


FIGURE 43. RECORDING BAROMETER
(*Courtesy Chicago Apparatus Company*)

tmospheric Temperature

The light and heat from the sun illuminate and warm the surface of the rth by day. Most of this heat is radiated in much the same manner that t bricks placed in a room warm the air of that room. The heat radiated m the ground is absorbed by the air of the atmosphere and for the most rt retained. In this manner the atmosphere acts as an insulating blanket. the absence of the atmosphere, the earth would be like the moon — ked by day and frozen by night. A large amount, perhaps half, of this at is retained or absorbed by the air. The degree or intensity of heat is lled *temperature*, the measurement of which will be discussed in detail in later chapter. Suffice it for the present to state that temperature is easured by the common glass thermometer, which is an instrument nsisting of a mercury-filled glass bulb sealed to a fine glass tube. As the mperature rises, the mercury expands and rises in the tube. The ther- meter is immersed first in a mixture of pure water and ice, and the height the mercury column marked; then it is immersed in the vapor of boiling ter and again the height is marked. If the interval between these two rks is divided into one hundred equal lines, each represents one degree temperature on the Centigrade scale, or 1° C. If the interval is divided to one hundred and eighty lines, then each represents one degree on the hrenheit scale, or 1° F.

The student is well acquainted with the temperature of the atmosphere. is announced over the radio daily, and it governs the amount of clothing at one wears. However, let us imagine a summer day at sea level with e temperature 90° F. or 32° C. Suppose one starts to climb a mountain goes up in an airplane. As the ascension continues, there is a decrease temperature at an approximately uniform rate of 6° C. per kilometer, 18° F. per mile. The temperature decreases up to 45,000 feet (eleven lometers), but at higher levels, in the stratosphere, it remains almost nstant.

The air is profoundly affected by heat. If the air over a region is heated, e whole mass of heated air expands and rises upward and overflows into adjacent mass of air which is at a lower temperature. Since the warmer r in rising expands or "thins out," there will be a lowering in the atmos- eric pressure. And because more air has flowed into the colder region, ere will be an increase in the pressure there, and as a consequence there ll be an underflow of air from the colder to the warmer region. The dif- rences in temperature between the two regions have produced differences atmospheric pressure, and as a consequence atmosphere circulation results.

tmospheric Circulation

The amount of heat received by the various regions of the earth, as dis- ssed under the topic of seasons in the last chapter, is vastly different.

In the equatorial regions the sun is overhead, and the rays almost perpen dicular; at the poles, owing to the inclination of the earth's orbit, the sun does not appear during a part of the year, and when it does shine it neve reaches an elevation of more than 23.5° in the sky. Since equatorial an polar regions are therefore at quite different temperatures, there is a tend ency of the warm air at the equatorial regions to be pushed up and flo toward the polar regions; and from the polar regions there is an under flow of the cold air toward the equatorial regions. The difference in tem perature gives rise to a difference of atmospheric pressure and, as a con sequence, movements of air masses from one region to the other. Whe the movement of the air masses is horizontal or nearly parallel to th earth's surface, it is known as *wind*; other motions of air are calle *currents*. The general tendency of movement of air masses from th equatorial regions upward and thence to the polar regions and of underflo from these cooler to the warmer regions is modified by several factors The most important are the effects of the earth's rotation on the movin of masses of air, the irregular distribution of land and water on the earth and the variation of the amount of heat received by the various layers o air — with the layer of air which is next to the earth's surface receivin most of the heat. As a result, atmospheric circulation is complex, an only the general trends will be described in this text. For more detaile account the student is referred to texts in meteorology.

Winds blow from all directions, and are designated by the direction o the compass from which they blow. A wind that blows from the nort east is known as a northeast wind. The velocity of winds varies from on to four miles per hour fo light breezes, from twenty five to thirty miles per hou for strong breezes, fifty t sixty for strong gales, an seventy-five and over for hu ricanes. The direction of th wind is determined by th familiar *weathervane*, while th velocity of the wind can b measured by an instrume called the *anemometer*.

FIGURE 44. GENERAL MOVEMENT OF AIR IN THE TROPOSPHERE

The various kinds of win as related to the general atmo pheric circulation outlin above are shown in Figure 4 The belt of equatorial regio called *doldrums* is in a lo pressure area. The air near t

ıt surface of the earth becomes warmed, expands, and is pushed upwards. ıe ascending warm air carries considerable moisture, and as it rises becomes cooled by expansion and the moisture condenses to form clouds ıd rain. This equatorial area extending in average width from one to ʏo hundred miles is characterized by calm weather, constant clouds, and ɔnsiderable rain. The ascending currents of air masses in the equatorial gions produce an underflow of air from the adjacent regions of higher at- ospheric pressure and give rise to the *trade winds*. These blow constantly ward the low-pressure region of the doldrums. If the earth did not tate, the direction of blowing would be from the north in the northern misphere and from the south in the southern hemisphere. But since e earth is rotating from west to east, the movement of the air masses is flected, and as a consequence the trade winds blow from a northeast rection in the northern hemisphere and a southeast direction in the uthern hemisphere. The warm air in the doldrums region as it rises ɔward moves in the upper atmosphere in the contrary direction to the ıde winds, north and south from the doldrums. Because of the earth's tation these *anti-trade* winds are deflected eastward until they finally ıvel at right angles to their original direction and settle down to the rth at about 30° north and south from the belt of the doldrums. These lts of high pressure are called *tropical calm* belts or "horse latitudes." ıey are characterized by clear skies and calm or light winds. The zones tending from 30° north and south to the vicinity of the polar regions are aracterized by winds which, although they have a general west-to-east rection, vary considerably both in intensity and in local direction. These nds are called *prevailing westerlies* and their direction is west and slightly uth in the northern hemisphere and west and slightly north in the south- ı hemisphere. The region of the prevailing westerlies is characterized changing weather and storms. The stormy weather is succeeded by r weather with a constant regularity. The changes in weather are ways accompanied by movement of large masses of air from west to st, and the path of these movements is of great importance to weather recasting. The polar regions, as previously noted, are characterized by v temperature and high atmospheric pressure. The winds blowing ɔm the poles have a general east-to-west direction, though, because of eater rotation at the poles, they form large rotating masses of air.

The general trend of the winds described above is affected by the revolu- ın of the earth in its orbit. With the alternation of the seasons, there is ange in temperature and shifting of the winds. The equatorial calm lts shift slightly, and so do the rainy seasons for such places as Ethiopia, e Philippine Islands, and many other regions. Where there are pre- iling westerlies, as in the United States, the changes are more profound. ıough there is a general trend to tropical weather in the summer and lar weather in the winter, the changes and variations of weather are

largely determined by the movements of warm air masses from the tropica regions and cold air masses from the polar regions.

Since the land becomes heated rapidly during the day and cools quickl at night, whereas water is slow to gain and lose heat, areas of high and lo pressures develop over land and sea. During the summer months area of high pressure and low temperature exist over the oceans in the temperat climates, and areas of comparatively high temperature and low pressur exist over continental masses. During winter the conditions are reverse Thus, the general trend of the polar-equatorial circulation is modified b the seasonal changes in the temperate climates to produce the season circulation which in turn determines the changes of weather.

Water Evaporation and Humidity

Water vapor continuously passes into the air from large bodies of wate from the ground, and from the surfaces of plants and animals. The amou of water vapor that the air can hold increases with the rise in its temper ture. For a given temperature this amount of vapor is definite, and b yond that point condensation begins. When such a point is reached, th air is spoken of as being *saturated*. The amount of water vapor und ordinary conditions is below the satu ration point, and the ratio of th amount present to the amount at th saturation point is called *relative hu midity*. For example, a relative hu midity of 75 in a room means that th air contains 75 per cent of the max mum possible amount that the air ca hold at the temperature of the roo The higher the relative humidity, th slower the rate of evaporation become Under such conditions, the coolin effect of evaporation from the surfa of the human body becomes negligib and the characteristic "sticky" feelin results. The temperature in a partic lar region may be 90° to 100° F. a the relative humidity 30 to 40. The conditions are comfortable, for the he is not noticeable. In another region, the temperature may be 80° to 90° and the humidity 60 to 80; summers in such a region are uncomfortab for most people.

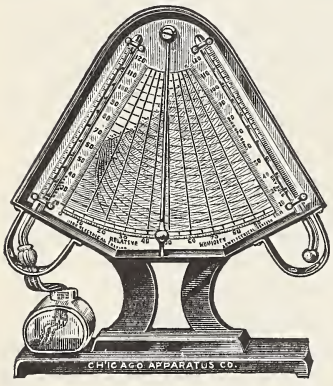


FIGURE 45.
A WET AND DRY THERMOMETER
(*Courtesy Chicago Apparatus Co.*)

The most common method of measuring relative humidity is through wet and dry thermometer (Figure 45). The bulb of the wet thermomet is wrapped in a piece of muslin which is kept wet by immersion in a ves

ntaining water. The temperature of the wet thermometer depends on
ıe rate of evaporation and hence on the relative humidity. For a given
mperature of the air, the wet bulb registers less than the dry by an
nount depending upon the relative humidity and the rate of flow of the
r over the bulbs. From the dry and wet bulb readings the relative
ımidity is read from a chart. Instruments for recording relative hu-
idity are constructed of bundles of human hair, which when carefully
eaned will extend about 2.5 per cent of its length when placed in an
mosphere saturated with water vapor. A bundle of human hair attached
a series of levers to transmit the motion to a moving pen is the essential
ement of the hygrograph, which records humidity readings on a drum
tated by clock work.

For rough measurements of relative humidity — that is, to determine
hether the humidity is simply high or low — use is made of catgut,
tton, paper, and other materials which change their characteristics with
sorption of moisture. Change in color, for example, may be used with a
per or cloth soaked in a solution of cobalt chloride and dried. When
e humidity is high, the color is pink, and when low, the color is blue.

ecipitation

Warm air moving upward carries with it water vapor from the constant
aporation of oceans, lakes, and streams and also of the water in the
ound; as the expanding air rises and cools, the water vapor passes from
e gaseous to the liquid state and condenses into minute droplets which
rm clouds and either fall slowly or are kept floating by rising currents of
. The droplets are very small, their average diameter being 0.01 of a
illimeter. Certain clouds found in the upper parts of the troposphere
e made up of ice needles. Clouds are classified according to an inter-
tional system into ten different types. These will be described briefly.
ıe abbreviations usually employed to designate them are given in
rentheses.

High Clouds: These usually occur at heights of 20,000 to 40,000 feet. *Cirrus* (Ci), thin featherlike structure, generally of whitish color: believed to consist of fine needles. *Cirrocumulus* (Ce), thin clouds, cottonlike or flakelike. *Cirrostratus* (Cs), very thin sheet clouds, giving the sky a milky appearance.

Middle Clouds: These usually occur at heights of 6000 to 20,000 feet. *Altocumulus* (Ac), large globular masses of sheeplike clouds arranged in groups or lines. *Altostratus* (As), a thick sheet of a gray or bluish color.

Low Clouds: These usually occur at heights from close to the surface to 6000 feet. *Stratus* (St), a uniform layer of cloud resembling a fog but not resting on the ground; stratus clouds are grayish, resembling a fog which has been lifted. *Nimbostratus* (Ns), low, amorphous, dark, with ragged edges from which steady rain or snow usually falls. *Stratocumulus* (Sc), large,

globular masses or rolls of dark clouds often covering the whole sky espe cially in winter.

CLOUDS OF VERTICAL DEVELOPMENT: These may occur at height of 150 to 30,000 feet. *Cumulus* (Cu), the most common clouds; they are thick wit a flat base and a domelike top that shines in the light. *Cumulonimbus* (Cb) heavy masses of clouds, usually in the form of mountains, with cirrus veil on top and a nimbus-like base.

The type of clouds present and the amount of sky covered by clouds a any particular time are of importance in weather forecasting. In weathe reports the term *clear* is used when less than one-tenth of the sky is covere with clouds; the term *partly cloudy* is used when between four- and seven tenths of the sky is covered; and *cloudy* or *overcast*, when more than eight tenths of the sky is covered.

Whenever condensation of water vapor occurs near the surface of th earth, it results in what is known as a *fog*. Some fogs are formed durin the night in quiet valleys and lowlands which are moist. By evaporatio during the day the air above the earth acquires considerable moisture During the night, if the temperature is lowered by loss of heat, condensa tion of the moisture in minute droplets occurs and a fog results. Suc fogs are visible in the morning, but disappear or become "lifted" soon afte the sun warms the air. More persistent fogs are formed when warm an moist air is blown over a colder region, as for example when a warm mois wind blows from the sea over a cold coastal region. The moisture become condensed to droplets and forms the dense fogs which are characteristi of Newfoundland and England. The water vapor present in the air ma be condensed on the earth in the form of *dew* or *frost* if the temperature the surface is lower than that of the surrounding air.

Rain results when the water droplets in the clouds unite rapidly to for larger droplets and eventually a size is reached which cannot be supporte by the rising air currents. It has been estimated that the largest drop about four millimeters in diameter and falls with a velocity of eighte miles per hour. Large drops fall with a greater velocity than small ar are broken up into smaller drops. During the summer, particularly hot days, evaporation is high. The ascending air carries with it conside able water vapor. As the air cools by expansion or contact with other co air, conditions are favorable for rapid condensation, so that, instead clouds, the characteristic summer afternoon showers result. The dro are big, for, the motion of the upward current being rapid, the dropl must increase in size considerably in order to fall. During the wint rains are of the fine, drizzling type. When water vapor condenses direct into the solid state, crystals of snow are produced, and several of the crystals adhere together and come down to the earth as aggregates call *snowflakes*. The condensation of water vapor occasionally takes place the form of hard pellets of ice called *hail* or *hailstones*. Hail is form

hen raindrops are carried to higher and colder regions by ascending cur-ents of air. They may grow in size by falling and accumulating more ater droplets and then being carried upward again.

Water reaching the ground in all forms is spoken of as *precipitation.* he amount of rainfall is measured by various types of rain gauges, and is sually expressed in inches. Thus the monthly and the annual rainfall an be recorded. It is obvious that the amount of rainfall is one of the ctors that determine the type of society inhabiting a particular region. n deserts the annual rainfall is about two to five inches and hence only a omadic society can develop, usually of herdsmen forever following their oving flocks in search of grasslands. Over the agricultural regions of the idwest the annual rainfall is thirty to forty inches. On the other hand, eath Valley, in California, receives but one to two inches per year.

ir Masses and Weather

The term *weather* denotes over-all effect due to the daily variations of tmospheric pressure, temperature, wind direction and velocity, humidity, oudiness, precipitation, and visibility. The various weather phenomena e due to the circulation of large *masses of air.* Due to the general cir-ulation pattern of the atmosphere, large masses of air tend to stagnate er certain areas of the earth's surface; during these periods of rest these ist masses acquire the characteristic properties, notably humidity and mperature, of the underlying surface. These widespread bodies of air e known as *air masses* and may be defined as *a vast portion of the atmos-ere whose physical properties are more or less homogeneous in its hori-ntal extent.* This means that the huge body of air has, approximately, e same temperature and moisture content throughout its entirety at ch level. Although the properties of an air mass are fairly constant, rizontally, the temperature and pressure diminish with height. The gions of the earth's surface where these large bubbles of air have stag-ted and have assumed uniform horizontal properties are called *source gions,* and are classified as: *polar continental, polar maritime, tropical ntinental,* and *tropical maritime.*

During the winter months the entire area from Alaska on the west to brador on the east and from the Arctic Ocean on the north to latitude ° on the south is the polar-continental source region of North America. uring this season the surface of this vast area, including the Arctic Ocean d Hudson Bay, is entirely covered by snow and ice, and the overhang-g air becomes very cold at the lower levels, giving rise to intense tem-rature inversions (increase instead of decrease of temperature with ight). Such an air mass is known as a stable air mass, and vertical otion of the air is suppressed. Since this air mass originates over a ozen, continental surface, the moisture content is very low, and hence uds and other forms of condensation are almost entirely lacking. Gen-

erally the polar-continental air mass is extremely stable, has very lo surface temperature and moisture content.

With the migration of the sun northward to as far north as 23.5° du ing the northern hemisphere's summer months, the surface of the pola continental source region is strongly heated by the sun, and the snow an ice disappears, leaving a typical land surface. As the result of this hea ing, moisture acquired at the surface is carried aloft and turbulence c instability causes a thorough mixing, making the moisture content unifor throughout. With the heating of the terrain, the lower levels of th atmosphere become very warm, giving rise to instability, that is, a greate decrease of temperature with height than the normal 5.3° F. per 1000 fee Therefore, in summer the polar air mass still has a low moisture conten its temperature is low compared to the air of lower latitudes, and it is a unstable body of air.

The source regions for polar-maritime air are the north Pacific an Atlantic Oceans. Since large bodies of water gain and lose heat ver slowly, there is only a small seasonal temperature change over these water Dry air from the intensely cold polar cap drifts over these ocean area and stagnates. The lower layers of air in contact with the warm ocea will be warmed and the capacity for moisture increased. Since th warmed air expands and becomes lighter, it begins to rise through th upper layers of cold and more dense air. The ascending air is cooled an the moisture it has picked up from the underlying water surface is co densed to form clouds and rain. The upward currents of warm moist a and the downdrafts of cold dry air cause considerable turbulence whi is called *instability*. The characteristics of a typical polar-maritime a mass are: (1) relatively warm temperatures and high moisture content the lower levels; (2) extreme turbulence or instability; (3) convective clou (cumulus and cumulonimbus); and (4) instability showers or precipitatio

Because of the narrow shape of the North American continent in t south, this area of the earth's surface is without a tropical-continent source region during the winter months, but with the northerly migrati of the sun above the earth's geographical equator the arid regions of t southwestern states and the north-central portion of Mexico become t source region for summer tropical-continental air. Here, polar-continen or polar-maritime air stagnates and the lower levels become highly heate giving considerable convective instability but a high cloud base becau of the low moisture content.

Tropical-maritime air originates in the high pressure belt of the nor Atlantic and north Pacific Oceans between latitudes 20° and 30°. He the underlying water surface has an average temperature of 75°, th creating an extremely warm air mass. The moisture content is extrem high in the lower layers, and there is a natural decrease of temperatu with height.

Air mass weather. Weather variations occur when one of the air masses ɔove leaves its source region, is carried along by the major circulation air, and displaces another air mass of totally different properties. Veather phenomena occur along the zone where these two air masses ıttle for supremacy. Less drastic weather changes occur within the air ass itself as the large bubble of air moves over varied terrain and slowly s properties become modified.

When the cold, stable, polar-continental air mass leaves its source gions and passes over the northern portion of the United States, the wer levels are heated by the warmer surface, and convective currents sult. But because of the low moisture content of the mass, few or no ouds are formed, and the visibility within the mass remains very good ıe to the slight turbulence created by the convective currents. During ıe winter months as the mass passes over the Great Lakes the lower vels are slightly warmed and will increase their moisture content. When ıis extremely unstable air reaches the southern shores of the lakes, stability showers develop, dropping out the newly acquired moisture in ıe form of snow. In general, fair weather accompanies a continental air ass. As this body of air moves south, it passes over the warm ɔouthern rrain and its lower levels are warmed. Increased heating during the ternoon will cause turbulence and cloud formation as the rising air cools. his will cease, however, as the sun sets and the clouds dissipate, leaving ear, cool nights.

The Pacific coast is under the influence of polar-maritime air at least 5 per cent of the time. In winter this warm air mass passes over the ɔld surface of the western seaboard and the lower layers are cooled and ıe instability ceases. As the moist air moves eastward, it is forced over ıe western mountain ranges, cooled by expansion, and the moisture con- ɛnt drained in the form of heavy rainstorms on the western side of the ıountain range. In summer, the cool maritime air mass is warmed over ıe land, the instability is increased, and convective showers frequently ɛcur.

By far the most important body of air is the tropical-maritime mass. he fertile Mississippi valley, the rich farm lands of the north-central ates, the productive wheat fields of Kansas and Nebraska, all owe their xistence to the repeated invasions of this warm, moist air mass. The ɛader will recall the incursions of the low moisture content polar-conti- ental mass, the short northeastward migration of the extremely dry ropical-continental air body, and the encroachment of the moistureless olar-maritime mass that precipitated its moisture on the Pacific side of ur western cordillera. As this air mass invades the North American con- nent through the Gulf of Mexico during the winter months, the tempera- ıre of the lower layers is greatly reduced as the mass comes in contact ith the wintery continental surface, and stability is increased. Deep

layers of fog may cover large areas, and if the wind velocities are high, th fog is dispersed and lifted to a low-ceiling stratus deck, and a stea drizzle may develop. When this warm mass advances northward over t warmer continental surface during the summer months, instability develo rapidly. If there is a wide difference between the air-mass temperatu and the surface temperature, air-mass thunderstorms will develop.

Fronts — Warm, Cold, Stationary, and Occluded

The air masses, upon leaving their source regions, are carried along the major circulation of air and begin their migration. In the mid latitudes or temperate zones, there is a constant battle between the pol air mass and the tropic air mass as to which shall dominate. The bat line at which these different air masses meet and engage in their neve ending tug of war is called a front. A front may be defined as *a surfa or zone of discontinuity between two dissimilar air masses.* This zone usually from five to fifty miles in width, and within this area a gradu transition from one type of air to another type takes place. Fronts a classified as (1) *warm front* — along which warm air replaces cold air; (*cold front* — along which cold air replaces warm air; (3) *stationary front* along which one air mass does not replace the other; (4) *occluded front* — front resulting when cold air overtakes a warm front.

Figure 46 shows a vertical cross section through a warm front. T warm air, displacing cold air, ascends over the cold wedge with resulti expansion, cooling, and very characteristic cloud formations. An approac ing warm front is first evident to the observer by the appearance of cirr clouds which are ice particles at an altitude of about 20,000 feet, whe temperatures are well below the freezing point of water. Since the slo of a warm front is about 1 to 300, at this stage the front is still about thr hundred and fifty miles away. As the warm front approaches, the clou change to cirrostratus, begin to lower to altostratus, rain begins to fa

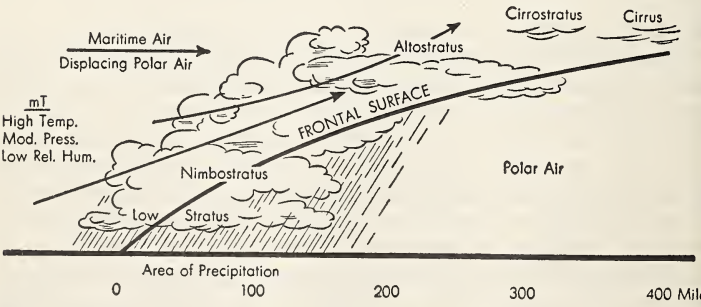


FIGURE 46. WARM FRONT

ıd the clouds lower still further to nimbostratus. The barometric pressure ;ops slowly, and as the front goes by at the surface, low stratus clouds ith steady precipitation predominate, since this is the area in which most the moisture content is removed from the air.

With the passage of the warm front, the barometric pressure will level f or rise slowly, the winds will shift to a southerly direction, the tem- ;rature and relative humidity will increase sharply, and warm weather, ıaracteristic of a maritime-tropic air mass, will be in prospect.

Figure 47 shows a vertical cross section through a typical cold front. s the cold air advances, it replaces the warm moist air, forcing the warm r upward where it cools, the moisture condenses, and cumulonimbus ouds develop. The slope of the cold front is between 1 to 40 and 1 to 80 ıd is much steeper than that of the warm front. The reason for this eepness is that the wind velocity increases with height and that friction tards the frontal movement at the surface of the earth, resulting in ster motion in mid-air than at the surface of the earth. As the cold ont moves forward, there are no clouds preceding its approach, since the ıld front slopes backward over the cold body of air. As the front ap- ;oaches an observer, the barometer drops sharply. Gusty winds, con- ;ctive clouds, and showers occur. After the frontal passage, the pressure ses, the wind shifts to a northerly direction, and both temperatures ıd relative humidity drop considerably. After a few brief showers, clear ıol weather can be expected. If the warm air is extremely unstable, olent thunderstorms may take place and the front is then called a squall ıe. To the airplane pilot this is the most dangerous type of front to fly ırough.

When a cold front overtakes a warm front, resulting in the lifting of one the fronts above the other, an *occluded* front is formed. If the air in ıe rear of the cold front is the colder of the two cold bodies, the warm ont is lifted above the surface of the earth. If the air in advance of the

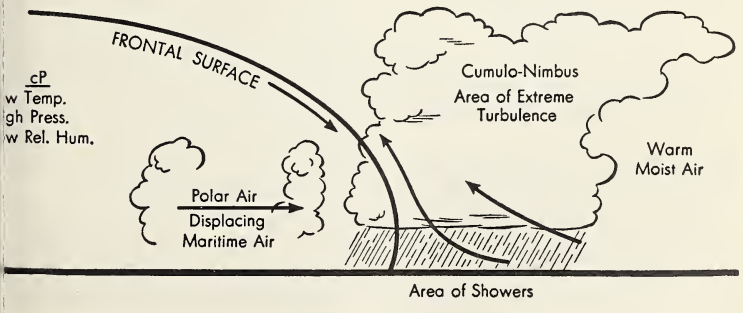


FIGURE 47. COLD FRONT

warm front is the colder of the two cold masses, a warm front type of occlusion develops, with the cold front over-riding the warm front.

Cyclones (Lows) and Anticyclones (Highs)

In the construction of weather maps the first step is to record the atmospheric pressure or barometric readings obtained from a large number of weather stations in the northern hemisphere. The next step is to draw lines which connect points having equal pressure; it will then be observed that the pressure field is divided into three smaller pressure areas, namely lows, highs, and cols. An area of low pressure is usually called a *depression*, *cyclone*, or *low*, and may be defined as an atmospheric circulation which is characterized by relatively low pressure at the center. After further study it would be noted that the winds circulate about the center in a *counter-clockwise* direction with a drift toward the middle of the pressure field. If the plotted pressure readings represented weather observations of stations located in the southern hemisphere, the same distinct divisions would be found but the circulation would be in the opposite direction or in a clockwise movement about the low center. Figure 48 shows a map view of a low; Figure 49, that of a high. The concentric lines called isobars represent surfaces of equal pressure. The arrows show wind direction and general circulation. The figures express the barometric values of equal pressure surface in millibars.

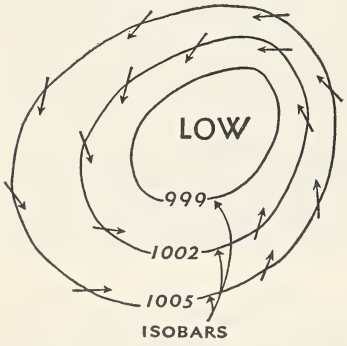


FIGURE 48. ISOBARS OF A LOW IN THE NORTHERN HEMISPHERE

If, to the barometric readings, data from other instruments of these weather stations were added to this map, and a detailed study of the cyclone were then made, various other features of this pressure field would be noted. It would be found that the cyclone is made up of two distinct air masses, separated from one another by a front. The southern portion is composed of air extending from a warm tropical mass toward the center of the cyclone. The warm tongue of air is usually surrounded by cold, polar air. Further study would show extensive cloudiness and much rain associated with this pressure pattern.

The second marked pressure pattern is one where the pressure at the center of a closed isobaric field is relatively higher than the pressure on the outskirts of this field. This area is known as an *anticyclone or high*. The wind flows spirally outward from the center in a clockwise direction in

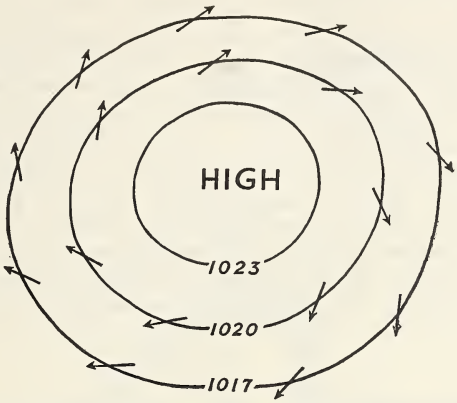


FIGURE 49. ISOBARS OF A HIGH IN THE NORTHERN HEMISPHERE

he northern hemisphere and in a counter-clockwise direction in the south-rn hemisphere. Winds are light and variable, and usually fair weather ccompanies a high pressure area.

The third pressure field found on the pressure map would be an area of niform pressure but not enclosed by isobars. This field is termed a *col* nd is always found between two cyclones and two anticyclones.

Figure 50 represents the various stages in the life cycle of a cyclone. 'he solid black arrows represent currents of cold air. The double-shafted /hite arrows represent the movement of the warm air. Diagram (*a*) epresents the boundary line between the southernmost portion of a cold, olar mass and the northernmost extent of a warm, moist, tropical anti-yclone. Here these two dissimilar air masses meet along a front, but this ront remains stationary because the air streams are parallel to the frontal urface. Soon a wave, resulting from a disturbance, will form along the liscontinuity surface as shown in diagram (*b*). This is the simplest form f a cyclone and consists of a cold and warm front with an area of low tmospheric pressure at their point of union. If no further disturbances nfluence this wave, it will ripple along the frontal surface as a wave ipples over a water surface, giving rise to rain as exhibited by the shaded egion of diagram (*b*). If this cyclone tends to deepen — if the pressure t the center begins to fall — the wave motion along the front is retarded, vith the result that the cold front begins to move closer to the slower noving warm front. When this occurs, the rain pattern increases in the old area, as shown in diagram (*c*).

The amplitude of the wave increases, and soon the cold front overtakes

the warm front, resulting in an occluded front as exhibited by diagram (*d*). Here the warm extended tongue of the southern anticyclone is beginning to be pinched off from its mother source. The warm sector is being lifted above the surface and the higher velocity winds of the upper levels distribute this warm air over a large area above the cold mass, with the results of an increased rain pattern. As the occlusion process continues, diagram (*e*), the warm surface sector continues to disappear until finally the occluded front dissolves, and the cyclone becomes a whirling mass of homogeneous air, as shown by diagram (*f*). Whether a cold or warm front type of occlusion develops during the life history of a cyclone depends on whether the air in the rear of the cold front is colder than the air in advance of the warm front. This has been explained in the foregoing section.

Analysis of Weather Maps

The weather map for November 2, 1948 (Figure 54) shows an air mass marked *cPk* over the southwestern part of the United States. This indicates that it is continental-polar air, colder than the surface over which it is moving. An occluded front extends from the low pressure center at the Missouri border to about Little Rock, Arkansas, where it divides into a cold front curving back to Brownsville, Texas, and a warm front through New Orleans, Louisiana. From the low there is also a small stationary front which extends through Tennessee, Georgia, and Carolina, and changing to a zone marked *frontogenesis* where a front is developing. This zone separates a mass of air marked *MT/CP* which is maritime-tropic air overriding continental-polar air from a modified *CP* air mass. Further north are two cold fronts that are simply dividing lines which separate a cold high pressure cell advancing from northwestern Canada and another cold high pressure cell north of Bangor, Maine. It will be noted that a rain belt, extending through the midwestern states, has greatly extended itself to the northeast during the next twenty-four hours (Figure 55).

In back of the cold front is clearing cool weather, with the rain zone advancing well ahead of the occlusion. The low pressure region is not too intense, as shown by the light winds and the relatively large distance between isobars. Within the twenty-four-hour period covered by the two maps it can be seen that altostratus and altocumulus clouds in advance of the front have changed to rain and stratocumulus clouds. The weather has also cleared rapidly through Arkansas and Mississippi.

This brief discussion gives an elementary summary of the methods used in weather forecasting. For a detailed discussion the student is referred to texts on meteorology in the list of suggested readings.

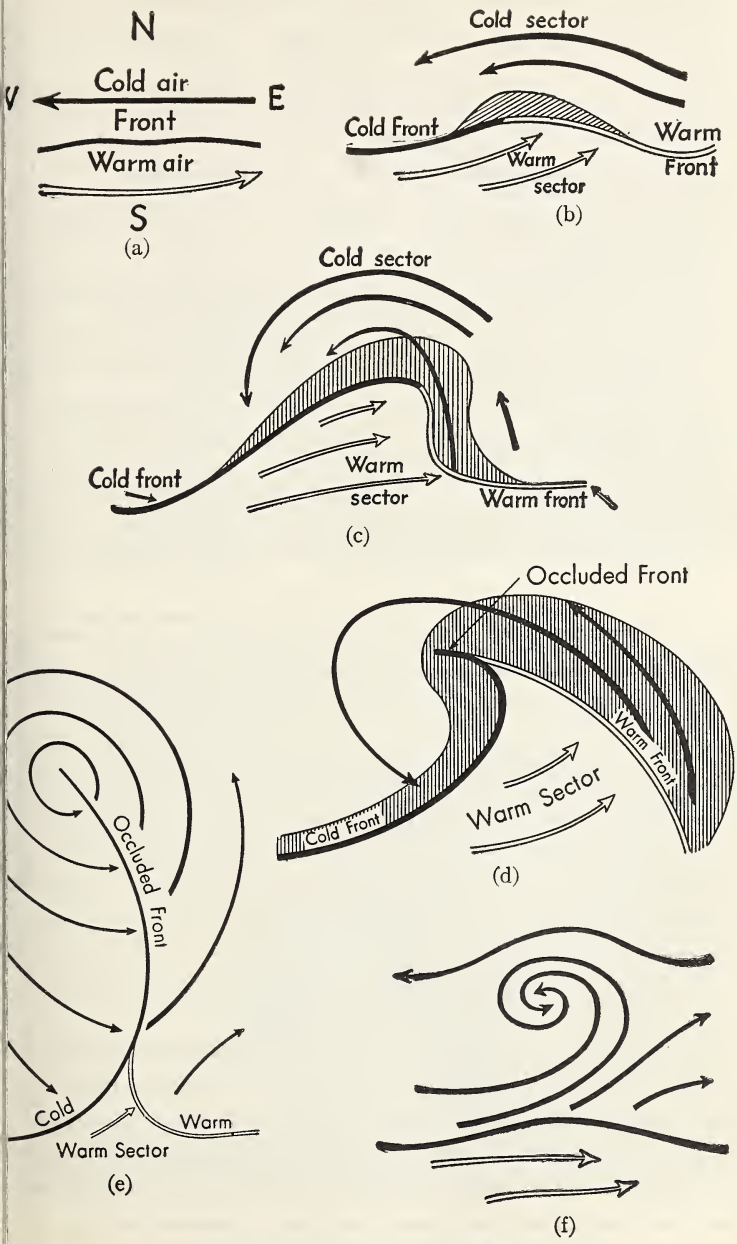


FIGURE 50. CYCLE OF CYCLONES

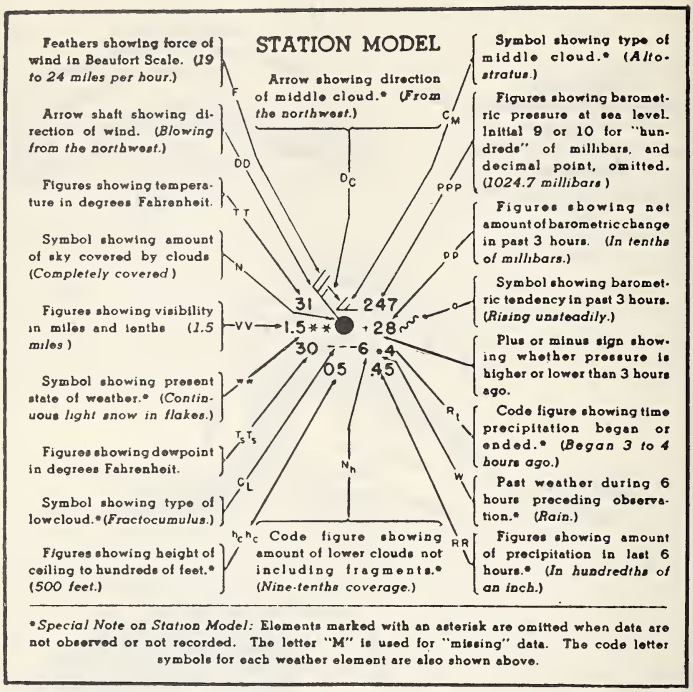

STATION MODEL
Feathers showing force of wind in Beaufort Scale. (19 to 24 miles per hour.)
Arrow shaft showing direction of wind. (Blowing from the northwest.)
Figures showing temperature in degrees Fahrenheit.
Symbol showing amount of sky covered by clouds (Completely covered.)
Figures showing visibility in miles and tenths (1.5 miles.)
Symbol showing present state of weather.* (Continuous light snow in flakes.)
Figures showing dewpoint in degrees Fahrenheit.
Symbol showing type of low cloud.* (Fractocumulus.)
Figures showing height of ceiling to hundreds of feet.* (500 feet.)
Arrow showing direction of middle cloud.* (From the northwest.)
Code figure showing amount of lower clouds not including fragments.* (Nine-tenths coverage.)
Symbol showing type of middle cloud.* (Alto-stratus.)
Figures showing barometric pressure at sea level. Initial 9 or 10 for "hundreds" of millibars, and decimal point, omitted. (1024.7 millibars.)
Figures showing net amount of barometric change in past 3 hours. (In tenths of millibars.)
Symbol showing barometric tendency in past 3 hours. (Rising unsteadily.)
Plus or minus sign showing whether pressure is higher or lower than 3 hours ago.
Code figure showing time precipitation began or ended.* (Began 3 to 4 hours ago.)
Past weather during 6 hours preceding observation.* (Rain.)
Figures showing amount of precipitation in last 6 hours.* (In hundredths of an inch.)
31
247
1.5
28
30
6
05
45
*Special Note on Station Model: Elements marked with an asterisk are omitted when data are not observed or not recorded. The letter "M" is used for "missing" data. The code letter symbols for each weather element are also shown above.

FIGURE 51. WEATHER MAP SYMBOLS: STATION MODEL

Beaufort No.	Miles per hour	Symbol	Forecast terms	Beaufort No.	Miles per hour	Symbol	Forecast terms	Beaufort No.	Miles per hour	Symbol	Forecast terms
0	Less than 1			5	19-24		Fresh	10	55-63		Whole Gale
1	1-3		Light	6	25-31		Strong	11	64-75		
2	4-7			7	32-38			12	Above 75		Hurricane
3	8-12		Gentle	8	39-46		Gale				
4	13-18		Moderate	9	47-54						

FIGURE 52. WEATHER MAP SYMBOLS: BEAUFORT SCALE FOR WIND DIRECTION AND VELOCITY

Cold front at the ground.
Cold front above the ground.
Warm front at the ground.
Warm front above the ground
Occluded front at the ground
Stationary front.

FIGURE 53. WEATHER MAP SYMBOLS FOR FRONTS

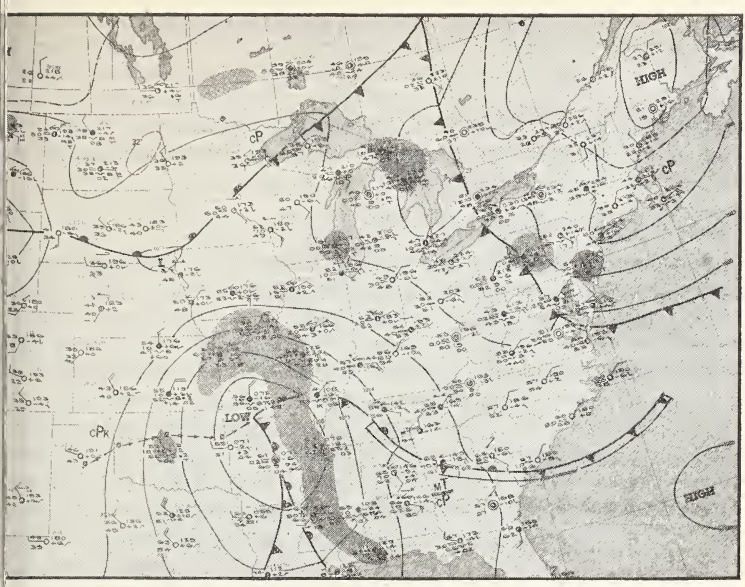


FIGURE 54. SPECIAL WEATHER MAP FOR TUESDAY, NOVEMBER 2, 1948

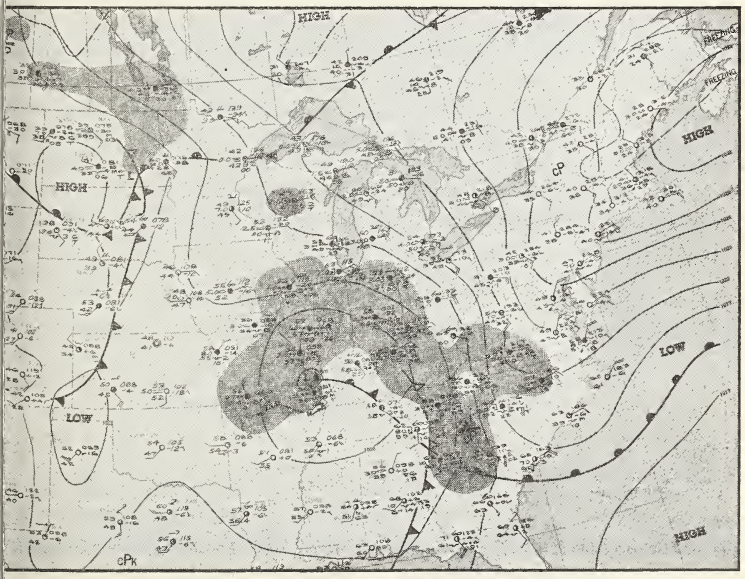


FIGURE 55. SPECIAL WEATHER MAP FOR WEDNESDAY, NOVEMBER 3, 1948

Weather forecasting is indispensable to air and sea transportation Airport weather stations are in operation at about fifty places primarily for airway service. In normal times weather reports are given over the radio and in the daily press. The warnings of frost and freezing weather are of great value to the farmer.

Hurricanes and Tornadoes

Hurricanes or tropical cyclones are vast stormy low pressure areas, the air revolving with great rapidity round a calm central core. The revolving winds reach velocities of one hundred to one hundred and fifty miles per hour. The pressure near the center is below 28.5 inches; hurricanes which have struck the coast of Florida have records of 27 and 26.5 inches. Hurricanes originate in the calm tropical regions in summer and in autumn as a result of local conditions which initiate a vigorous displacement of warm moist air by cold dry air arriving from higher latitudes. The cyclones usually have a diameter of three hundred to six hundred miles, and their approach is indicated by a continuous falling of the barometer, followed by winds of increasing intensity, until the center of the storm is reached when there is a short lull for less than an hour. The storm then begins anew, the wind changes to the opposite direction, and the pressure rises again. After about twenty-four hours the storm has passed.

A tornado or "twister" is a revolving storm of short life and great intensity, having a funnel of rising air in the center. Tornadoes are similar to tropical hurricanes, but of much smaller proportions. A funnel-shaped cloud develops, and when it reaches the earth it moves destructively along its path. The whirling low depression area consists of a cloud of water droplets and dust that it picks from the ground. It usually extends about a thousand feet in cross-section and travels twenty to forty miles per hour. It occurs frequently in Kansas, Missouri, Iowa, Texas, Arkansas, and Illinois, and less frequently in other states. It travels mostly from southwest to northeast. Aside from the destruction of the whirling motion of the wind which often attains a velocity amounting to upward of two hundred miles per hour, there is the bursting and lifting effect of the center of the tornado. Walls of buildings collapse outwardly and heavy objects are lifted and carried considerable distances. The cause of tornadoes is assumed to be the whirling upward motion produced at the boundaries of cold and warm air masses of greatly different temperatures.

Climate

The general weather conditions of a particular region make up its climate. It is well known that the equatorial regions are too warm and moist for any extensive human habitation. In the United States there are many desert regions which are too arid for any plant growth and are therefore not suitable for the establishment of any permanent community

The climate of a particular region has a profound influence on the culture f the men who inhabit it. It is no accident that the earliest civilizations eveloped in subtropical climates along river systems — the Nile in Egypt, nd the Tigris and the Euphrates in Mesopotamia. Today the most dvanced industrial civilizations are not in subtropical climates, but in older, temperate climates. Examination of a small globe of the earth with eference to the regions in which the most active civilizations exist disoses some pertinent facts. It will be seen that most of the industrial vilization today is concentrated in belts which make up only ten per cent the total area of the earth. The remainder is either too warm and moist, o cold, or too arid to support any extensive civilization. Although sevral million people inhabit these other belts, the climatic conditions do not ermit the growth of an active industrial civilization such as exists here nd in the principal European countries.

The general climatic zones, based on latitude, are: (1) equatorial, (2) ubtropical, (3) temperate or intermediate, (4) polar. These zones, howver, do not give a true picture of the climate, since the weather of any articular region may be modified by several factors, such as its elevation, nd the relative distribution of land and water in and about it. A person ay live in a region five degrees from the equator, but ten thousand feet bove sea level and have frost in the morning even in summer. Therefore, here are climatic variations independent of the latitude. The elevation the region and its position with reference to oceans, continents, and ountains give the region certain characteristics. On the basis of these fluences there are: (1) continental climates, (2) marine and coastal imates, (3) mountain and plateau climates.

The interior of continents is characterized by light rainfall, low humidity, nd clear weather. In the tropics there is little contrast between winter nd summer. In the temperate zones winters are cold and summers hot. the polar regions the winters are severe and prolonged, and summers e short. Large bodies of water gain and lose heat slowly; consequently, e climate of coastal regions and islands is moderate in changes. In the ountains and plateaus the conditions are determined by the elevation. p to about eight thousand feet the rainfall increases with the elevation; uring the day the temperature may rise rapidly, but at night cooling is so rapid. Above ten thousand to twelve thousand feet the conditions e too severe for any prolonged human activity.

In the highly specialized industrial civilizations, there has been a trend ward producing an ideal working environment through elimination of eather variation by air-conditioning. This is an attempt to create our eather indoors in order to eliminate extreme variations. When the temerature is too high, the air is cooled by refrigeration; when it is too low, is heated. The relative humidity is regulated, and the air filtered to move the dust. The bulk of humanity, however, still considers weather

a factor to be reckoned with in daily life and hence an inexhaustible topic of conversation.

SUMMARY

1. The atmosphere is the gaseous envelope that surrounds the earth. The water covering the earth constitutes the hydrosphere. The lithosphere is the solid portion of the earth.
2. The lower part of the atmosphere is called the troposphere, the upper, the stratosphere.
3. Nitrogen and oxygen make up the bulk of the gases of the atmosphere, the rest being small amounts of water vapor, rare gases, carbon dioxide, and dust particles.
4. Nitrogen and oxygen are elementary substances, or elements, that is, substances which cannot be decomposed by ordinary methods.
5. The height of the atmosphere is estimated by the scattering of sunlight and by the observation of meteors or "shooting stars."
6. The gases of the atmosphere have mass and hence exert pressure. The atmospheric pressure at sea level may be expressed as: 1033.6 grams per square centimeter, 76 cm of mercury, 29.92 inches of mercury, or 1013.2 millibars. The pressure diminishes with the altitude.
7. The barometer is an instrument for measuring atmospheric pressure and is also used for measuring altitude.
8. Temperature is the intensity of heat and is measured by a thermometer. One degree Centigrade is 1/100 of the difference in intensity of heat between the freezing and boiling points of water. One degree Fahrenheit is 1/180 of the same difference.
9. Air is greatly affected by heat, expanding and rising when warmed. Difference of temperature between two regions produces differences in the atmospheric pressure and is the primary cause of atmospheric circulation.
10. Movements of air masses parallel to the earth's surface are winds. The various kinds of winds are related to the rising of air in the equatorial regions and its settling down at the polar regions. The wind belts are: the doldrums, the trade winds, and the prevailing westerlies and prevailing easterlies.
11. Relative humidity is the ratio of the amount of moisture present in air to the amount required for saturation.
12. Water vapor, depending on atmospheric conditions, precipitates as cloud, fog, dew, frost, rain, snow, and hail.
13. Weather denotes the prevailing state of atmospheric pressure, temperature, wind direction and velocity, humidity, cloudiness, precipitation, and visibility.
14. An air mass is a widespread body of air approximately homogeneous in its horizontal extent and having the properties of the regions over which it has remained for some time.
15. The air masses of importance for the weather of North America are the co

polar continental and polar maritime and the warm tropical continental and tropical maritime.

5. The various air masses, with their source characteristics, move as a result of the general atmospheric circulation and become modified by the region over which they pass and determine its weather conditions.

7. A front is the surface which marks the boundary between a cold and a warm air mass. Cold fronts displace warm air and warm fronts displace cold air.

8. The pressure fields (highs and lows) generally move from west to east. The lows move counter-clockwise in the northern hemisphere, and the highs clockwise. Lows generally are associated with cloudiness and precipitation, and highs with light winds and clear skies.

9. Weather forecasting is accomplished by observations at six-hour intervals at many stations over the United States, which identify and report the various air masses, their movements and their relation to each other, and the location and movement of the fronts.

10. Climate is the term for general weather conditions obtaining in a region over a relatively long period of time.

STUDY EXERCISES

1. Draw accurately a diagrammatic picture of a barometer. What is the most convenient liquid suitable for use in such an instrument?

2. The altitude of Pike's Peak, Colorado, is 14,109 feet above sea level. Consult the data for barometric pressure in this chapter and estimate the barometric pressure at the top of the peak, (*a*) in cm of mercury, (*b*) in inches of mercury, (*c*) in millibars. Measuring from the top of Pike's Peak, what is the weight in grams of the column of air (recorded as cylindrical with a base area equal to 1 square centimeter and height equal to the topmost point above the earth) above this point?

3. Fill in the following table with reference to the atmosphere portion of the earth:

Data	Troposphere	Stratosphere
1. Approximate fraction of total mass of atmosphere		
2. Begins at height (miles above the earth)		
3. Ends at height known by measurements (miles above earth's surface)		
4. Characteristic regional conditions		
5. Approximate temperature of region		
6. Approximate composition		

4. By means of isobars, make a drawing of a high and a low, and underneath it place the following information in tabular form: (*a*) variation of pressure from center to the outer portion of the moving mass of air; (*b*) usual dimensions and rate of movement across the United States; (*c*) the type of motion and whether it is inward or outward; (*d*) usual weather associated with highs and lows in winter and summer.

5. Draw an outline map of the United States and trace on it the main routes taken by highs and lows as they sweep across the country.
6. If the barometer stands at a height of 756 mm of mercury, calculate the height at which water would rise if it were used instead of mercury. Give at least two reasons why it is not used.
7. Define the following phenomena and briefly explain the conditions under which each is formed:

fog	dew	snow	wind
frost	cloud	rain	hurricane

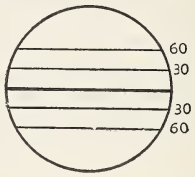
8. In the following diagram, identify (with arrows and names) by regions:

a) prevailing westerlies

b) northeast trade winds

c) southeast trade winds

d) horse latitudes



9. Consult the weather maps for the last three consecutive days and calculate roughly the distance a high has swept across the country. Do the same for a low. Calculate the velocity. What prediction can be made for the next three days?
10. Discuss the effect of climate on the type of civilization that develops in a given region.
11. Select the alternative that best completes each of these statements:

.... With increased altitude the temperature normally (*a*) increases; (*b*) decreases; (*c*) does not change.

.... With increased altitude the air pressure (*a*) increases; (*b*) decreases; (*c*) does not change.

.... Evaporation stops when the relative humidity is (*a*) high; (*b*) low.

.... A sea breeze usually blows during the (*a*) day; (*b*) evening in summer.

.... In the trade-wind belt (*a*) daily rains; (*b*) cyclonic rains; (*c*) many desert areas, occur.

.... High-pressure areas move across the United States from (*a*) E. to W. (*b*) N.E. to S.W.; (*c*) W. to E.

.... In the middle latitudes the air moves from areas of (*a*) high; (*b*) low pressure towards the polar regions of high pressure.

FOR FURTHER READING

1. Blair, Thomas Arthur, *Weather Elements.* New York: Prentice-Hall, Inc., 1937.

A college textbook in meteorology. The general discussion of the atmosphere will be found in Chapter 1. Atmospheric temperature and pressure is discussed in Chapters 5 and 6. The topics of weather forecasting, air masses, fronts, lows and highs, will be found in Chapter 10.

PETTERSSEN, SVERRE, *Introduction to Meteorology.* New York: McGraw-Hill, 1941.

A presentation of the subject in an elementary manner intended for students without previous acquaintance with meteorology. A general discussion of the atmosphere will be found in Chapter 1. Air masses and fronts are discussed in Chapters 7 and 8; Chapter 9 discusses the pressure fields. Weather chart analysis and weather forecasting will be found in Chapters 11 and 12.

BYERS, HORACE ROBERT, *General Meteorology.* New York: McGraw-Hill, 1944.

A college textbook on meteorology with particular attention to the operation of aircraft.

TAYLOR, GEORGE F. *Aeronautical Meteorology.* New York: Pitman Publishing Corporation, 1941.

A practical book that may be used by the general student in meteorology. A general discussion of the atmosphere is given in Chapter 1. Chapter 5 is a general discussion of air masses; Chapters 6, 7, and 8, a thorough discussion of air masses of the northern hemisphere. Chapter 9 is on fronts. The topics of the weather chart, weather chart analysis, and forecasting will be found in Chapters 17, 18, and 19.

ALBRIGHT, JOHN GROVER, *Physical Meteorology.* New York: Prentice-Hall, Inc., 1939.

A college textbook in meteorology. A general discussion of the atmosphere is given in Chapters 1 and 2. Atmospheric pressure and temperature are discussed in Chapters 3, 4, 5, and 6. The discussion of clouds and precipitation in general will be found in Chapter 8. The recent developments in the study of air masses and fronts will be found in Chapter 16.

HAYNES, B. C., *Meteorology for Pilots.* Civilian Aeronautics Bulletin No. 25. Washington, D.C.: Government Printing Office, 1940.

A concentrated practical discussion of meteorology as related to the operation of aircraft. Used in the training of civil aeronautic pilots. A general discussion of the atmosphere is given in Chapter 1. The topics of clouds and precipitation will be found in Chapter 4. Air masses and fronts are discussed in detail in Chapters 7, 8, and 9. Weather forecasting will be found in Chapter 15.

7

The Crumbling Rocks

IN THE PRECEDING CHAPTER the atmosphere and its most common change were considered with particular attention to those aspects which affect th daily life of man. Changes of the atmosphere, however, affect the lifele as well as the living world; the atmosphere is one of the agents that is co stantly changing and shaping the face of the earth. The present chapte will deal with the effects of the atmosphere on the inanimate world.

The Rocks of the Earth

In moist climates the surface of most land is covered with vegetatio Beneath this vegetation there is loose material consisting of soil, clay, san and broken rock, known collectively as *mantle rock*, best seen in deep cu or at the banks of streams. This layer varies from a few inches to sever hundreds of feet in thickness, and rests on solid rock known as *bed roc* which can be reached by digging or drilling. In some places the mant rock consists of the same materials as the bed rock, a fact indicating that was derived by crumbling and decay of the bed rock beneath. In oth places the mantle rock is quite distinct from the bed rock. This indicat that the mantle rock has been detached from rocks in other places an transported by such agents as streams, glaciers, wind, or gravity. Som times the mantle rock is absent and solid rocks are exposed. This is co mon on slopes of steep valleys and mountains, on cliffs which face seas lakes, and in the channels of swift streams. The appearance of most e posed or outcropping rocks does not at first examination present man features which would be of aid to the beginner in their classification an study. The difficulties, however, are due mostly to a lack of knowled of where and how to begin and of the tools to be used in the inquiry.

We have seen that the first step in any scientific inquiry is to assemb and classify the facts. It is advisable to begin the study of rocks by a examination of various samples, seeking to discover similarities or thin which they have in common. For example, it is possible to separate a assortment of rocks into light, buff, and dark groups and proceed to invest gate other common properties in each group. By scratching with an iro

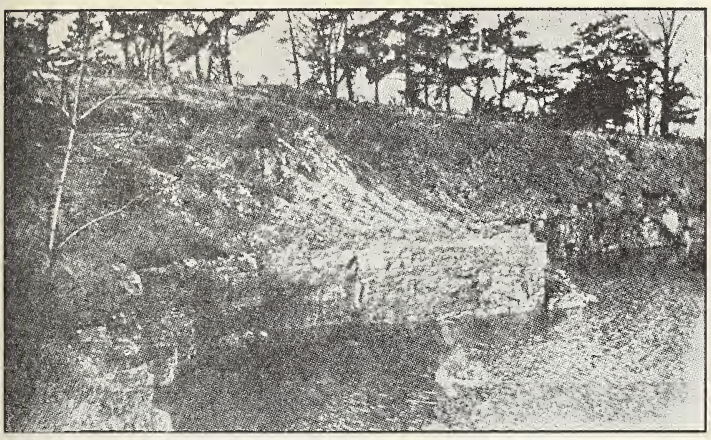


FIGURE 56. MANTLE ROCK AND BED ROCK

The soil and loose material (mantle rock) is usually derived from the bed rock. In this se, however, the mantle is of glacial origin and therefore not related to the limestone which rms the bed rock. (Courtesy of Illinois State Geological Survey)

il, we can further subdivide our rocks into those that are very hard and ose which are of medium hardness or soft. Examination through a magfying glass will disclose that all rocks are composed of individual particles cked very closely together. Usually the shape and color of the invidual particles are not the same throughout, and the conclusion may be awn that rocks contain more than one ingredient. In other words, they e aggregates of different things. At this point it becomes necessary to troduce new names, for it is difficult to proceed in any inquiry without ming new things as they are observed. The small individual particles ich are packed together to make the rocks are called *crystals*; occasionly a small sample of a rock will contain throughout the same kind of ystals. The individual crystalline particles are called *minerals*.

ssection of a Piece of Granite

When a piece of granite, such as shown in Figure 57, is examined through magnifying glass, it appears to be composed of white crystals called *artz*, buff-colored crystals called *feldspar*, and dark crystals called *mica*. is possible by means of a hammer and chisel to break granite into small rticles and then, with the aid of forceps and a magnifying glass, to separte its various minerals.

The characteristics by which the minerals are examined and identified e not elaborate and do not require much equipment. Minerals have a finite crystal structure, which means that they are solids bounded by

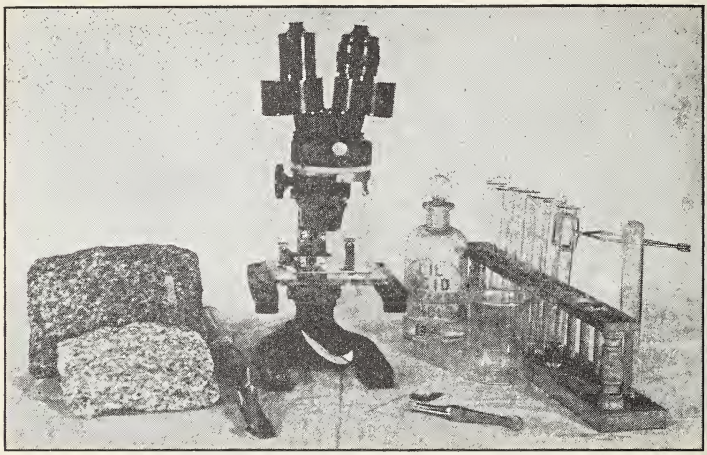


FIGURE 57. THE STUDY OF A PIECE OF GRANITE

smooth surfaces and well-defined angles. All crystalline forms conform to certain requirements of symmetry and are divided into six classes, the cubic, the hexagonal, etc. Minerals have a characteristic color and *streak*. The color is easily determined; the streak is the marking of the powdered mineral on unglazed porcelain. Many minerals have a tendency to break along certain planes, as, for example, mica; this tendency is called *cleavage*. Minerals have varying degrees of hardness between the extremes of talc and diamond. The hardness is generally designated by comparing it with Mohs's scale of hardness, in which ten minerals are arranged in increasing hardness, from talc as number one, to diamond as ten.

As soon as we have made a collection of various minerals, it becomes desirable to inquire further into their composition, seeking to discover common relations among them, as between quartz and feldspar, for example. This problem is difficult, and we must seek the help of a chemist who performs more complicated operations than those which were described above. Such operations — typical observations and conclusions — are summarized here:

1. A piece of granite occupies a definite space; when put on a table or on level ground it is stationary.

Conclusion: It is formed of *matter*; it has *mass* and *inertia*.

2. When heated to a high temperature in an enclosed space, so that any gases that may form cannot escape, it is found to retain its original mass.

Conclusion: This rock, like all matter, cannot be destroyed by any known amount of heat.

3. It is hard and tough, the finger cannot be pushed into it, it is difficult to drill or pierce with a nail.

Conclusion: It is a *solid* of considerable hardness.

4. One piece has a mass of 310 g. When it is placed in a graduated cylinder containing 500 cc of water, the level of the water rises to 610 cc. Other tests, however, with similar specimens, do not give the same result.

Conclusion: The volume of the rock is 110 cc and it has a density of 310/110 = 2.8 g per cc. The variations show that the density of granite is not constant.

5. When placed in water the rock does not dissolve, even after boiling, its mass is 309.9 g.

Conclusion: It is insoluble in cold water; in boiling water its solubility is very slight: approximately 0.1/310 = 0.03 per cent.

6. When heated to 1000° C. it remains a solid.

Conclusion: This substance has a high melting point.

7. When examined carefully with the naked eye — or better with the aid of a magnifying glass — it appears to be made up of black crystals (mica), grayish crystals (feldspar), and white crystals (quartz). The three types of crystals are not evenly distributed.

Conclusion: Granite is not a *pure* substance, but is a *mixture* of three or more pure substances. It has not the same composition throughout.

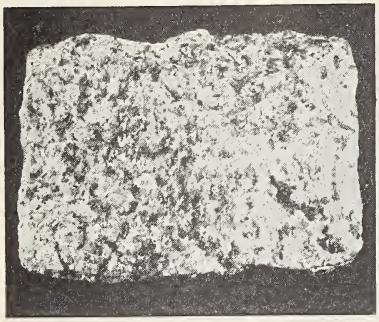
8. When crystals of quartz are separated out by means of a small chisel under a magnifying glass, they appear to be uniformly six-sided. Their density is found to be 2.65 g per cc. Numerous samples yield the same results.

Conclusion: Quartz is a pure substance, apparently homogeneous and of a constant density.

9. When quartz is powdered, mixed with a certain amount of aluminum powder in a clay crucible, and then ignited, a brilliant fire results. The whole mass melts and glows white hot, when cooled, the aluminum and quartz are no longer there. Instead, a white powder remains, identified as aluminum oxide, and a gray, crystalline solid. Since we suspect that there may be some aluminum in this solid, we suspend it in hydrochloric acid and thus remove the aluminum by dissolving it. The grayish crystalline solid has a density of 2.4 g per cc and melts above 1400° C. It is the element *silicon.*

Conclusion: Quartz is a *compound substance* or, as chemists say, a *compound.* Compounds (*a*) are pure substances, (*b*) have definite properties, such as density and color, (*c*) are homogeneous, or the same throughout, (*d*) usually cannot be separated into simpler pure substances by ordinary means, such as by mere heating or pounding, and (*e*) may be separated into simpler substances, called *elements,* by *chemical reactions.*

10. All attempts to change silicon into another element by chemical reaction fail. When 1.00 g of crystalline silicon is placed in a tube and



(*a*)

(*b*)

(*c*)

(*d*)

FIGURE 58

(*a*) *A Specimen of Granite. The minerals it contains are shown in* (*b*), (*c*) *and* (*d*) (*b*) *Quartz Crystals.* (*c*) *A Feldspar* (*Orthoclase*). (*d*) *Mica Sheets.*

heated while oxygen gas is passed over it, it burns, and the result is 2.14 g c white material identical with powdered quartz. When 100 g of powdere quartz are heated with aluminum, 46.6 g of crystalline silicon are obtained

Conclusion: Elements cannot be destroyed by chemical reactions. Ele ments combine to give compounds. The amount of silicon in quartz i definite, since 1.00 g of silicon burns in oxygen to give 2.14 g of quartz, th percentage of silicon in quartz is 46.6. When quartz is broken down b heating with aluminum, it yields 46.6 per cent of silicon. Hence com pounds have a constant composition. Quartz is a compound of silico and oxygen, and its chemical name is *silicon dioxide.*

Mixtures, Compounds, and Elements

The conclusions reached are found to agree with thousands of observa tions and experiments relating to the behavior of matter. Objects whic

e found in nature, in the whole world of matter, are usually *mixtures* of *ure substances*, and these pure substances are mostly compound sub-ances, or *compounds*. All compounds may be resolved by appropriate ethods into elements. Before any further probing is done on the piece granite under observation, it will be well to summarize what has been arned thus far about matter in its various forms:

1. Matter, like all fundamental concepts, cannot be defined except in rms of its properties.

2. Matter occupies space and has mass; since it has mass, it has inertia, stays put.

3. Matter in its changes is neither destroyed nor created.

4. The various forms of matter that fill the world are mostly mixtures. hese (*a*) are heterogeneous, that is, made up of different substances each which retains its identity; (*b*) have properties which are intermediate etween those of the individual particles of which they are composed — r example, some granites are more white because they contain more uartz; (*c*) can be separated by physical means into their components, ithout necessitating the conversion of even a small amount into another nd of matter; (*d*) are not constant in composition.

5. Mixtures can be separated into pure substances, which may be either mpounds or elements.

6. Substances (*a*) are homogeneous (same throughout); (*b*) have defi-te properties, which in the compounds are different from those of the ements of which they are made up; (*c*) if compound, may be broken down y appropriate chemical means into the elements of which they are com-osed.

7. Compounds always have a constant composition. This means that ne sample of a pure compound is exactly like every other sample in its nemical composition. Quartz from many different sources always con-ins 46.66 per cent silicon and 53.34 per cent oxygen. Therefore, *elements mbine to form compounds in constant ratios.*

8. Elements cannot be separated into simpler substances by ordinary nemical or physical means.

By appropriate chemical analyses the composition of the other two inerals isolated from the sample of granite rocks can be determined. eldspar contains oxygen, 45.9 per cent; silicon, 30.3 per cent; potassium, 4.1 per cent; and aluminum, 9.7 per cent. When it is considered that eldspars make up about one-half of the rocks of the earth's crust, an im-ortant conclusion appears: the elements out of which the bulk of the earth's rust is made are few and of these oxygen and silicon appear to be the most bundant.

he Abundance of Elements

Figure 59 shows diagrammatically the relative abundance of elements in

the crust of the earth. This indicates that most elements are exceedingly rare. Fewer than twelve elements comprise 99 per cent of the earth's crust.

Inspection of the diagram indicates that oxygen and silicon are the most abundant. The amount of these two elements is very nearly the same as in feldspars. Oxygen is not only the most abundant element in the outer veneer of the lithosphere, but also exists (combined with hydrogen) to the extent of 88.9 per cent in water and (in the free state) to the extent of about 21 per cent in the gases of the atmosphere. It should be noted that in the atmosphere it occurs in the free elementary form, but in both the hydrosphere and the lithosphere it is in combination with other elements. Table 10 shows the composition of the earth's crust and also the composition of the hydrosphere, the atmosphere, and the earth's crust combined.

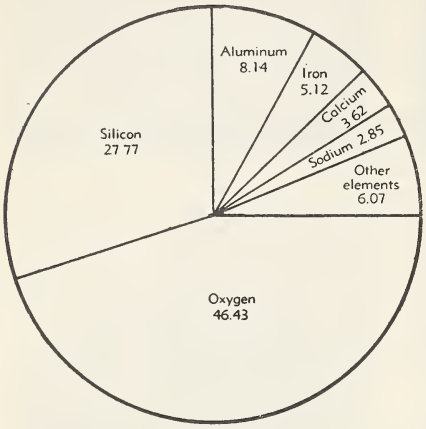


FIGURE 59. PERCENTAGE COMPOSITION OF THE EARTH'S CRUST

TABLE 10. COMPOSITION OF THE EARTH'S LITHOSPHERE, HYDROSPHERE, AND ATMOSPHERE

Element	Composition of Earth's Crust	Composition of Earth's Crust, Hydrosphere, and Atmosphere
Oxygen	46.43%	50.02%
Silicon	27.77%	25.80%
Aluminum	8.14%	7.30%
Iron	5.12%	4.18%
Calcium	3.62%	3.22%
Magnesium	2.24%	2.08%
Sodium	2.46%	2.36%
Potassium	2.46%	2.28%
Titanium	0.63%	0.53%
Hydrogen	0.22%	0.95%
All others	0.91%	1.28%

It should be realized that this table refers only to the known portion of the earth, which does not exceed ten miles in depth. The composition of the earth as a whole, though not known directly, appears to be vastly different

Classification of Elements

The number of elements is usually given as ninety-two, although re

ently four elements have been synthesized, neptunium, plutonium, curium, nd americium, which increases the number to ninety-six. A list of all the ele- nents will be found inside the front cover and on page 420. Those in italics re to be noted, as they will be used frequently in the discussion of the phys- cal world.) The names of elements, like the names of animals and people, ollow no general rule. Those known in antiquity were not many: copper, arbon, gold, iron, lead, mercury, silver, sulfur, and tin. The other ele- nents were discovered after the seventeenth century, with the exception of few discovered by medieval alchemists. Elements are named after colors iodine), odors (bromine), countries (gallium), etc. Their symbols as mployed today are useful abbreviations, and the beginner is encouraged o learn this simple shorthand for the most important elements. For ex- mple, it is easier to write *I* than iodine. Similarly, *Cl* is used for chlorine. ometimes the symbols are derived from the Latin or Greek word for the ame elements. For example, *Na* from the Latin *natrium* signifies sodium, nd *Ag* from the Latin *argentum* indicates silver. It should be emphasized hat symbols and formulas are a shorthand method of notation; knowledge f the symbols alone is of no particular value, but they are extremely use- ul in describing transformations of matter.

The elements are usually classified into *metals*, *non-metals*, and *inert gases*. 'he basis of this classification is certain common characteristic properties. t should be pointed out that the term properties may indicate such *hysical* properties as color, density, solubility, crystal structure, taste, uster, and hardness, or *chemical* properties — the behavior of a particular ubstance toward other substances. For example, iron rusts in moist air nd gold does not. The rusting of the one and the absence of rust in the ther are chemical properties of iron and gold. A certain group of sub- ances, including acids, is usually used to test the behavior of other sub- ances; these are called *reagents*. For example, copper foil looks almost the ame as gold foil; the easiest method to differentiate them is by the action f nitric acid, which dissolves copper but leaves gold unaffected. During ne process of observing a chemical property, some of the matter being udied is changed into other quite different forms of matter. This kind of hange is called a chemical change. In a physical change the kind of matter ersists unchanged, though its state may be changed; in a chemical change ne original kind of matter disappears and new and different kinds appear n its place.

The division of elements into metals and non-metals came very early. t was noted that iron, copper, silver, and gold are heavy and possess metal- c luster, ductility, and malleability, whereas sulfur, carbon, chlorine, and xygen are light and have none of these characteristic metallic properties. 'onsequently the elements were arranged in these two groups. When, ter, the rare gases of the atmosphere — helium, neon, etc. — were dis- overed, it was found that these elements did not combine with others to

Table 11. Classification of Elements

Properties	Metals	Non-Metals	Inert Gases
Characteristic state...	hard solids.....	gases or brittle solids.	gases
Density.....	high.....	low.....	lowest
Melting point.....	high.....	low.....	lowest
Metallic luster.....	present.....	absent.....	none
Ductility, malleability	good.....	poor or none.....	none
Conductance of heat or electricity.....	good.....	poor.....	poor
Chemical behavior towards oxygen.....	Most metals combine to form oxides....	Most non-metals combine to form oxides.	Do not combine

form compounds; hence they were called inert gases and placed in a group by themselves. The classification is not a very sharp one, for many elements possess both metallic and non-metallic properties. On the other hand, it should be realized that classifications are man-made devices to facilitate study, and that in nature we meet usually with gradual transitions from one extreme to another, whether it be day and night or oxygen and iron. It will be found convenient to study Table 11, which summarizes the characteristic properties of the three groups of elements.

It will be noted that the table is a summary of the preceding discussion except for the last property — the behavior of metals and non-metals toward oxygen.

The Common Minerals

Several hundred minerals are known, but most of these are not very common. The bulk of the known part of the lithosphere is composed of a few complex minerals which in Table 12 are listed in italic type.

Table 12. Common Minerals

Mineral	Elements Present	Chemical Name
Simple Minerals:		
Quartz	Silicon, oxygen	Silicon dioxide
Hematite	Iron, oxygen	Iron oxide
Magnetite	Iron, oxygen	Magnetic iron oxide
Corundum	Aluminum, oxygen	Aluminum oxide
Calcite	Calcium, oxygen, carbon	Calcium carbonate
Pyrite	Iron, sulfur	Iron sulfide
Complex Minerals:		
Feldspars: Orthoclase	Silicon, oxygen, aluminum, potassium	Potassium-aluminum silicate
Ferromagnesians:		
Pyroxenes	Silicon, oxygen, calcium, iron, magnesium	Calcium-iron-magnesium silicate
Micas	Silicon, oxygen, potassium, aluminum, hydrogen	Potassium-hydrogen-aluminum silicate
Olivine	Silicon, oxygen, magnesium, iron	Magnesium-iron silicate

Inspection of the table shows that a simple mineral is usually a compound of oxygen with another element and hence is called an *oxide*. If the oxide is derived from a metal, like iron oxide, it is a *metallic oxide*; if the oxide is derived from a non-metal, like silicon dioxide (quartz), it is a *non-metallic oxide*. If the lower part of Table 12 is examined, it will be seen that the complex minerals may be regarded as complex compounds of silicon or *silicates* derived by the combination of the non-metallic silicon dioxide with one or more metallic oxides. For example, feldspars, which contain the elements silicon, oxygen, aluminum, and potassium, may be regarded as complex silicates containing silicon dioxide together with the metallic oxides of potassium and aluminum. Likewise, pyroxenes are composed of silicon dioxide and the oxides of calcium, iron, and magnesium. It should be understood that the names *feldspars*, *pyroxenes*, *micas* refer to groups of minerals which are closely related.

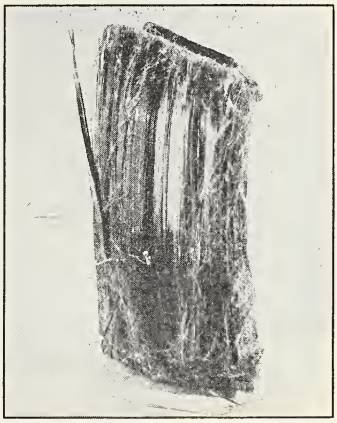


FIGURE 60.
ASBESTOS, A HYDRATED MAGNESIUM SILICATE OF FIBROUS STRUCTURE THAT BREAKS INTO FIBER-LIKE THREADS

The Mode of Formation of Rocks

Close examination of various rocks discloses two general types. In the first type the crystalline structure indicates that they were formed by solidification of molten matter which originated within the earth. The crystals of one mineral may be large, those of another smaller, and those of a third, squeezed together in spaces left between other crystals, indicating that these were the last ones to form, and filled the spaces which were left. Such formation is known to occur today in many volcanoes of the world where discharged streams of lava flow from the interior of the earth and slowly cool to form rocks. These rocks, on account of their mode of formation, are called *igneous*. The molten matter may rise from the depth of the earth to higher levels and cool slowly before reaching the surface, forming *intrusive* igneous rocks; those that form near the surface from lava issuing from volcanic vents are called *extrusive*. The most common example of igneous rock is granite, which forms the core of many mountains. As we have seen, even a superficial examination shows that it is a mixture of crystals of quartz, mica, and feldspar.

The second group of rocks shows many layers, with the individual particles not very compact. Shells and imprints of sea animals indicate that

FIGURE 61. SEDIMENTARY BEDS OF NIAGARAN LIMESTONE SHOWING STRATIFICATION
(*Courtesy of Illinois State Geological Survey*)

these rocks were formed by deposition of sand, mud, and other sediments in the seas and lakes. Sandstone, shale, and limestone are characteristic of this group, called *sedimentary* rocks. From these two general types of rocks arises a third, when either igneous or sedimentary rocks are altered by high pressures and temperatures within the crust of the earth. Since they have been altered, they are called *metamorphic* rocks. An example of this class is slate formed from shale.

Common Igneous Rocks

The most important igneous rocks and their general characteristics are listed in Table 13. The size of the crystals of granite indicates that the rock crystallized very slowly from the molten mass of minerals. If the molten mass had been near, or had flowed upon, the surface, the rate of cooling would have been rapid and the resulting rock would have very fine crystals or even a glossy appearance. Hence the inference is drawn that granite must have formed at great depths where the insulating effect of the overlying rocks permitted slow cooling and therefore differentiation of its various minerals in large crystals. Rhyolite has approximately the same composition as granite, but was formed from molten rock at or near the surface. The relatively rapid cooling results in a fine-grained rock which has small crystals. When the cooling has been very rapid, the rock is composed entirely of glass and is called *obsidian*. Both granite and rhyolite are light in color, since they contain more silicon dioxide, or quartz. Gabbro and basalt contain little quartz and an excess of ferromagnesians and

Table 13. Common Igneous Rocks

light color ↑	Formed at great depths: coarse-grained; large crystals	Silicon Dioxide ↑ increases	Formed at or near the surface: fine-grained; small crystals
	Granite (quartz, mica, feldspar)		*Rhyolite* (composition same as granite)
	Diorite (feldspar, ferromagnesian, quartz)		*Andesite* (composition same as diorite)
dark color ↓	*Gabbro* (ferromagnesian, some feldspar)	↓ decreases	*Basalt* (composition same as gabbro)

or this reason are dark. Diorite and andesite contain an intermediate amount of silica, much feldspar, and some ferromagnesians.

The granites are found in the Rockies and in practically all mountain systems; large rhyolite flows are found in the Yellowstone region. Andesites occur in many places. The Colorado Canyon at Boulder Dam is of andesite flow. Basalt on cooling forms characteristic columnar structures and is found in many regions.

Common Sedimentary Rocks

Sandstones, limestones, and shales are familiar sedimentary rocks formed by deposition of the broken fragments and débris of older rocks. Under the combined effect of the atmospheric forces, solid rocks are constantly crumbling to smaller fragments, which are being continuously transported and deposited as sediment. These changes have been going on continuously from the remote past down to the present. Water evaporates from the oceans and is swept far inland, to fall eventually as rain or snow. Then the long journey of this surface water through the soil and through flowing streams begins — a process which continues until the water reaches the sea again, but now carrying with it a vast amount of suspended débris and dissolved minerals, which eventually settle and later harden to form sedimentary rocks. Wind and glacial ice also act as transporting agents of broken rock which is dropped and accumulated as sedimentary deposits.

Sediments accumulate from minerals carried in solution, or from broken rock material, such as gravel, sand, silt, and clay. The coarse sediments are dropped first, and therefore the usual deposition as we proceed outward from the shore of a sea or lake is gravel, coarse sand, fine sand, and fine clay. This order may be disturbed by the shifting of the sediments through wave action or by lowering or elevation of the sea level, so that fine material may alternate with coarse. This gives the outstanding characteristic of sedimentary rocks — the *stratified* structure. The *strata* or layers vary in thickness, color, texture, and composition. Each stratum is separated from the one above and below by a plane which is called the stratification plane, and it represents a change in some character of the sediment. As

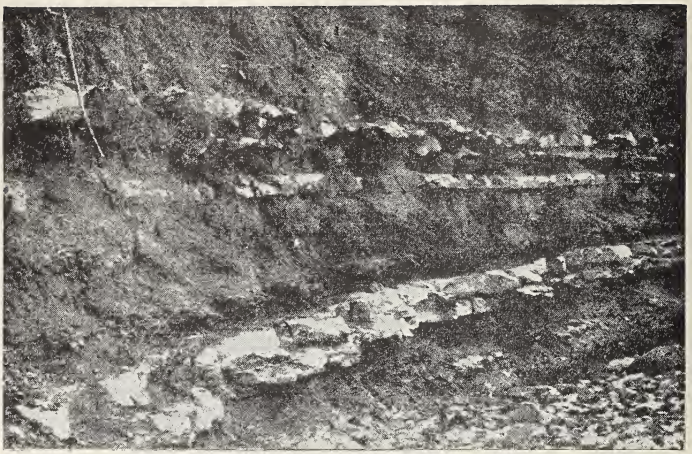


FIGURE 62. ALTERNATION OF LIMESTONE AND SHALE
The limestone strata are more compact and harder than shale
(*Courtesy of Illinois State Geological Survey*)

FIGURE 63. CANYON WALL OF CONGLOMERATE
Parfrey's Glen, Baraboo, Wisconsin

FIGURE 64. CLOSE-UP OF CONGLOMERATE
Same canyon wall shown in Figure 63

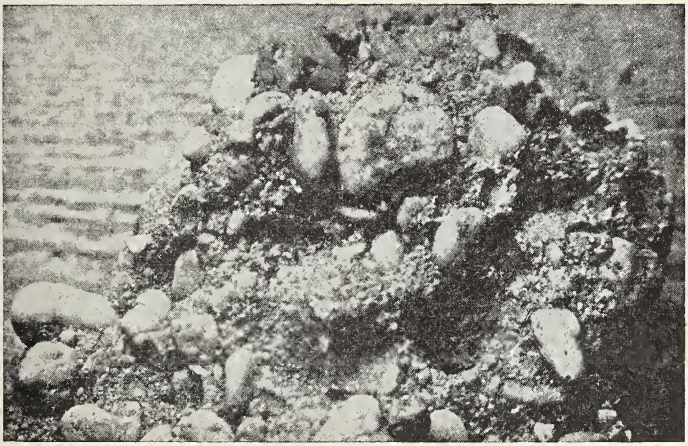


FIGURE 65. CLOSE-UP OF CONGLOMERATE
Four-fifths of natural size. (*Courtesy of Illinois State Geological Survey*)

Table 14. Common Sedimentary Rocks

Sedimentary Rocks	Nature of Unconsolidated Sediments
Conglomerate and breccia	Gravel (pebbles or boulders)
Sandstone	Sand grains (quartz)
Shale	Clay (mud)
Limestone (limestone, marl, chalk)	Limy mud, calcareous sand, shell fragments
Chert, flint	Finely divided silica which may have been deposited from solution
Coal	Plant remains

the beds increase in thickness, the pressure of the overlying beds compresses the lower beds, making them more compact. As the beds sink, water slowly passes through the pores and deposits from solution calcium carbonate or other substances, which thus act as cementing material. Figures 62, 63, 64, and 65 show various types of sedimentary rocks. Table 14 lists the most common sedimentary rocks and the character of the sediments which were involved in their formation. The dissolved material is discharged, or is precipitated, by changes in temperature and pressure or by chemical reactions of the solution. Marine life removes calcium from the water to form shells, which are later deposited as sediments. The sediments from broken rock material are chiefly transported by running water and drop as horizontal deposits when the velocity of the stream diminishes.

Common Metamorphic Rocks

All metamorphic rocks were originally igneous or sedimentary, but have had their original character changed by high temperatures and enormous pressures within the earth's crust. Around the borders of igneous intrusions, older rocks are baked, hardened, and altered. The changes are more intense in the immediate vicinity of the zone contacting the igneous mass, and less so away from it. For example, limestone, when it is intruded by an igneous mass, changes from a dull rock to brilliant, snow-white marble. The organic material in the limestone is expelled, and the fine grains of calcium carbonate recrystallize into larger crystals. The heat may also be produced as a result of the rock movements to which deeply buried rocks are subjected by the weight of the overlying rocks. Pressure may also be exerted on rocks that are not deeply buried by the folding of strata into arches as a result of *diastrophic movements*, which include the displacements of one part of the lithosphere with respect to another. In metamorphism of this kind the rocks are deformed, stretched, and compressed; pebbles are elongated; crystals are rotated so that they lie with their long axes in the direction of least pressure and offer minimum resistance.

Both igneous or sedimentary rocks may be altered into *slates*, *schists*, or *gneisses*. The slates, formed from shales, basalts, and other rocks, break easily along planes parallel to the elongation of the rock; the crystals of mica which form during the alteration of the original rock are very small.

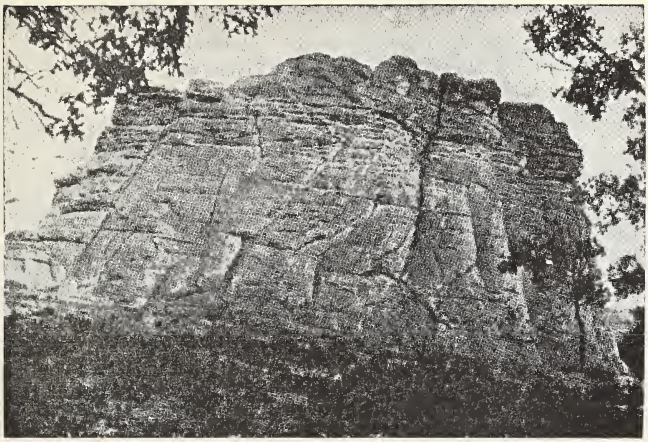


FIGURE 66. ROCK OF WHITE SANDSTONE
Standing on the bank of Rock River, Illinois

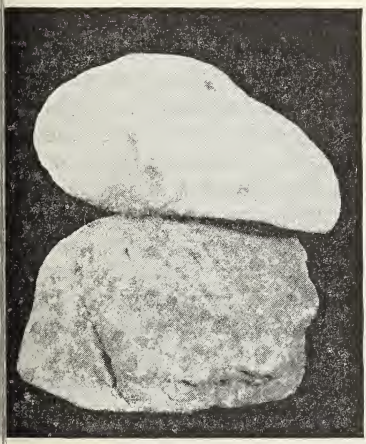


FIGURE 67. WHITE SANDSTONE (STARVED ROCK, ILLINOIS) AND COLORED SANDSTONE (MISSISSIPPI BANK NEAR MARQUETTE, IOWA)

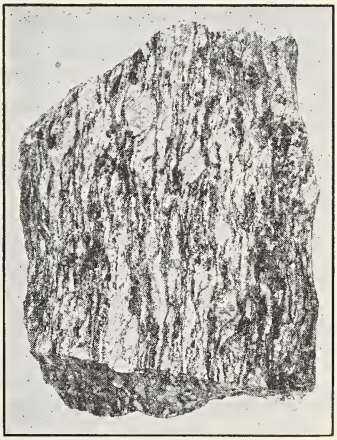


FIGURE 68. A SPECIMEN OF GNEISS
Biotite gneiss formed by strong metamorphism. The banded appearance is due to the flow of minerals as a result of pressure.

TABLE 15. COMMON METAMORPHIC ROCKS

Igneous and Sedimentary Rocks	Metamorphic Equivalent
Granite	Granite gneiss
Rhyolite	Rhyolite schist
Andesite	Hornblende schist
Basalt	Slate, biotite schist, etc.
Shale	Slate, mica schist
Limestone	Marble
Sandstone	Quartzite
Bituminous	Anthracite, graphite

and the cleavage surfaces are planes. Thus mica schists result when the mica crystals in metamorphosed slate become so large as to be seen as flakes by the eye. Gneisses have a foliated or banded structure resulting if the rock contains considerable feldspar, as does granite. Table 15 lists the common igneous and sedimentary rocks and the metamorphic type to which they are usually altered. It should be noted that the first conversion of limestone and sandstone results in marble and quartzite. Quartzite is no longer porous, and the fractured surface does not reveal the grains of the original rock. Pore spaces have been eliminated by enlargement of the sand grains through precipitation of silicon dioxide from solution which seeps through rocks. Both quartzite and marble on further alteration can give rise to schists.

Weathering of Rocks

Mention was made at the start of this chapter of the fact that the atmosphere is responsible for extensive changes on the face of the earth. In order to study this activity, the nature and composition of the rocks have been considered. The changes, though very slow if measured by the span of a human lifetime, nevertheless are extensive. No matter how strong the solid rock or how permanent the hills and mountains may appear, all slowly crumble to fragments which are constantly being moved away toward the sea. This continuous alteration of the face of the earth by the crumbling of rocks and transportation of the débris is called *erosion*. The first step in the general process is the "chiseling out" and decay of the solid rock into smaller fragments. This process, called *weathering*, is accomplished mostly by the atmosphere.

The changes and factors involved in weathering are complex and need not be considered in detail. They may be divided into the physical action of *disintegration* to particles of smaller size and the chemical action of *decomposition* in which the complex minerals of the rocks undergo profound changes. Both of these actions occur at the same time, although one may predominate over the other because of local conditions. In arid regions mechanical disintegration is more pronounced, and in moist regions chemical changes predominate.

isintegration of Rocks

Heating by day and cooling by night produce changes in rocks similar to ose resulting from the sudden heating or cooling of glass. Strains are veloped in the rock which result in cracks and in the shattering of large asses into fragments. This effect is rticularly noticeable in mountain aks. The alternate expansion and ntraction of the outer part of the ck pulls it away from the inner part, aving a new surface for repetition the "shelling off" process, which called *exfoliation*. An example of foliation on a grand scale is found the white granite of Yosemite Na- nal Park.

When the temperature falls below C., the water in the pores and cracks rocks freezes and exerts considerable essure, since it expands about one- venth of its volume. The effect is ore noticeable in porous rocks, such shales and sandstones, whose pores count for ten to twenty-five per nt of their volume. Repeated freez- g and thawing near the edges of ffs and in mountain-tops disrupt and slodge small and large blocks of ck.

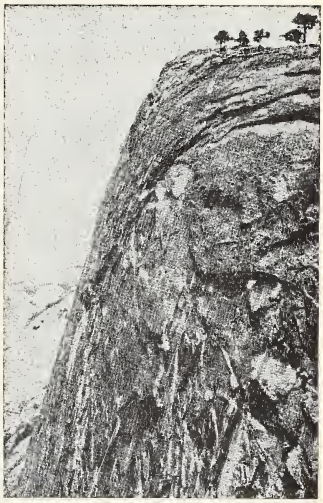


FIGURE 69.
EXFOLIATING GRANITE
In Yosemite Valley
(*Courtesy of U.S. Geological Survey*)

FIGURE 70. BLOCKS OF GRANITE LOOSENED BY FROST
(*Courtesy of U.S. Geological Survey*)

Aside from the disintegrating effects of changes in temperature, rock are cut and slowly broken down by the small particles of rock which are blown by the wind. As discussed in the previous chapter, the velocity of the winds varies. Light breezes move with a velocity of ten to fifteen miles per hour, strong breezes with a velocity of thirty to forty miles per hour. As the gaseous mass travels over the surface of the earth, it removes large quantities of earthy material, dust, and even particles of sand. In this manner, particularly during the summer and in periods of drought, large quantities of soil are removed from the land, giving rise to the familiar dust storms. Though the heavier particles of sand are not transported very far, they are blown over rocks and erode their surfaces through *abrasion*. This "sandblast" action is more noticeable in arid and semi-arid regions, where it sculptures the rocks into grotesque forms of pinnacles, needles, and table rocks.

Decomposition of Rocks

A piece of iron exposed to moist air ultimately crumbles to a soft powder called rust. Chemical examination of the new substance shows that it consists of a mixture of iron oxide, part of which contains water (or is *hydrated*) and some iron carbonate. In other words, the rusting of iron is a chemical combination between the iron and three of the gaseous or vaporous components of the atmosphere: oxygen, water, and carbon dioxide. The process, then, may be described as *oxidation*, *hydration*, and *carbonation*. In exactly the same manner as the hard iron changes to flaky rust, the minerals in the hard rocks undergo chemical combinations with oxygen, carbon dioxide, and water. The iron silicates in such minerals as mica and other ferromagnesians combine slowly with oxygen to form yellow or brown stains of iron oxide on the rock. Finally, after the rock has been pulverized to soil, the oxidation continues and thus the red, brown, and yellow colors of soil develop. Another agent aiding in the chemical alteration of rocks is the acid action of ground water. As rainwater falls from the atmosphere to the ground, it dissolves some carbon dioxide to form carbonic acid. The amount of acid in ground water is further increased from the organic acids produced by the decay of plant and animal matter. The minerals of the rocks in the upper part of the lithosphere are continually being subjected to this acid action of ground water. Carbonic acid combines with metallic oxides, yielding such carbonates as potassium carbonate and calcium carbonate. Since a number of these carbonates are soluble, ground water carries away many minerals in solution and thus produces pits, holes, cracks, and caves in rocks.

The process of hydration is shown in the hydration of quicklime and plaster of paris. It involves a chemical combination of a substance with water, with the result that the hydrated substance has different properties from the original. The hydration of rocks aids in their disintegration

FIGURE 71. WEATHER PITS ON GRANITE
(*Courtesy of U.S. Geological Survey*)

FIGURE 72. JOINTED GRANITE
In the High Sierras. (*Courtesy of U.S. Geological Survey*)

For example, the feldspar in granite is changed by hydration to kaolin, o clay. It should be realized that oxidation, hydration, and carbonatio may proceed simultaneously, thus complicating the process enormously.

A number of other factors assist in the disintegration and decompositio of the rocks, though to a smaller extent. The roots of plants grow int cracks and crevices and push rocks apart. Animals, such as earthworms ants, and rodents, burrow into the land and loosen it. Bacteria are ver abundant in soils and on bare rocks. Decaying plants produce carboni acid and other acids which attack the rocks. Man does his part in ex cavating road cuts and tunnels, in mining, and in cultivating the lan The breaking of the sod, the clearing of brush and timber, and the destroy ing of forests by fire and lumbering have permitted rapid erosion.

It should be realized that all of these actions are modified by variation i climate, in topography, and in the resistance of the rock. It is this *differ ential erosion* that has produced the many landscape features that tourist travel far to see. The deserts present an awe-inspiring spectacle of ba vertical cliffs sculptured in many patterns and colored in many hues. I humid regions the decomposition of rock proceeds more rapidly than i arid regions, resulting in the familiar rounded hills with smooth slope covered in most places by soil and vegetation.

Soils. The products of weathering in some places are carried away b the transporting agents as fast as they are formed. In others, particular where weathering is rapid, as in cliffs with steep slopes at a high altitud the loosened débris accumulates at the base of the cliff to form slopes calle *talus.* Disintegrated rock is present in all places of the land as *mantl* its upper part, which can support vegetation, is called *soil.*

Soils may be derived from the bed rock; when they are, there is a gradu transition downward in the mantle to the bed rock. Soils of this type a called *residual.* In other cases the soil is derived from mantle that w transported by water, wind, or glaciers, and hence is called *transport* soil. The thickness of the soil varies from a few inches to many feet.

The upper part of soil which has supported vegetation for some time black (humus soil), chiefly from the decomposition of organic matte Soils vary in character and texture, depending on the mantle from whi they were derived and on the extent of bacterial changes within the Soils derived from granitic mantle contain an abundance of clay and a co siderable amount of sand particles. Shales and limestone yield soils of cl rich in calcium carbonate. At first the disintegrated mantle suppor scanty vegetation. This is seen when the dirt dug from a basement fi to six feet deep is spread over an empty lot. Only a few virile weeds gr during the first year. As these weeds decay over the winter, some orga material is added to the soil. The bacteria begin to multiply, and the s begins to be *organized.* The water percolating through the soil remov some of the fine clay, carrying it below, thus producing a less compact ma

FIGURE 73. CLIFF AND TALUS SLOPE
Wayne County, Utah. (*Courtesy of U.S. Geological Survey*)

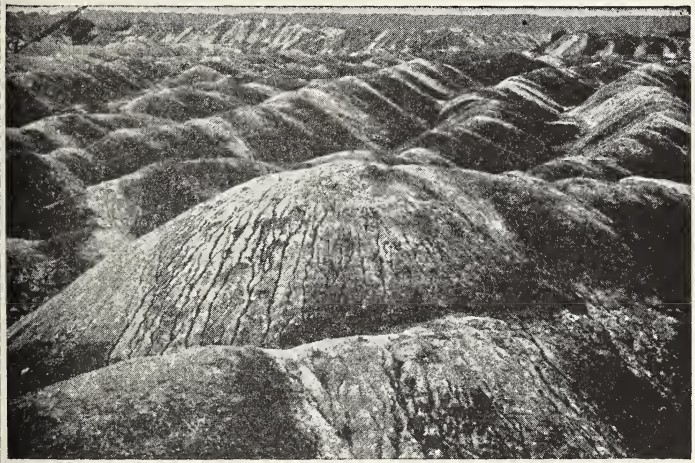


FIGURE 74. DUMPS COMPOSED OF MANTLE FROM STRIP MINES
Near Utica, Illinois. No vegetation grows on this loose earth, as it has not yet been organized into soil.

Finally, the top soil, dark in character, develops. The conditions are no static but dynamic; in other words, change and activity continue. The rains continue to dissolve and carry away necessary constituents such a calcium carbonate; unwise cultivation and grazing may lead to a washing away of the top soil until erosion has rendered the farmland incapable of supporting vegetation. True soil erosion may remove both the top soil and subsoil so that new bed rock may be exposed. The process of soil formation may then begin anew, but it will take thousands of years. For this reason the conservation of soil by the prevention and checking of soil erosion is receiving wide attention.

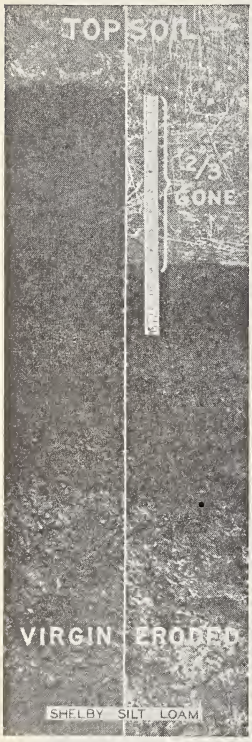


FIGURE 75.
COMPARISON OF VIRGIN SOIL AND ERODED SOIL
(*Courtesy of U.S. Department of Agriculture*)

A brief consideration will show the importance of soil to the welfare of the community. In several parts of the United States one may travel from districts which show the well being predominant in most communities to regions of abject poverty and squalor. The visitor must leave the roads and travel on foot. Close observation will show that poverty and squalor are not due to the laziness of the inhabitants, but to the inability of the soil to yield a decent livelihood. The early settler found a virgin soil beneath the huge forest which they cleared away, and since there was plenty of land and an apparently eternal frontier to move to, they did not worry about conservation. They cannot be blamed, for they did not know, for example, that the soil of the valley of Sparta in Greece, cultivated for over three thousand years, today does not support wheat much above a foot in height. Government activity in soil conservation, although lately begun, promises to remedy this situation.

Transportational Work of the Atmosphere

In addition to its weathering effect, the atmosphere acts both as an agent of erosion and as an agent of transportation through the effects of the wind. The abrasive action of the wind-borne particles of sand against the surface of rocks has been mentioned. The wind acts as an agent of transportation by rolling the heavier sand particles and carrying in suspension the lighter dust particles. Dust caught in an upward current is carried over great

ghts and transported to great distances; dust from the explosion of canoes has been observed to travel around the world. The dust eventu- is deposited as a fine-grained sediment called *loess*. Vast areas of rope, Asia, and North America are covered with deposits of loess; it ns in masses of varying thickness without horizontal stratification, and ietimes forms high bluffs in valleys. Many deposits of loess are found in

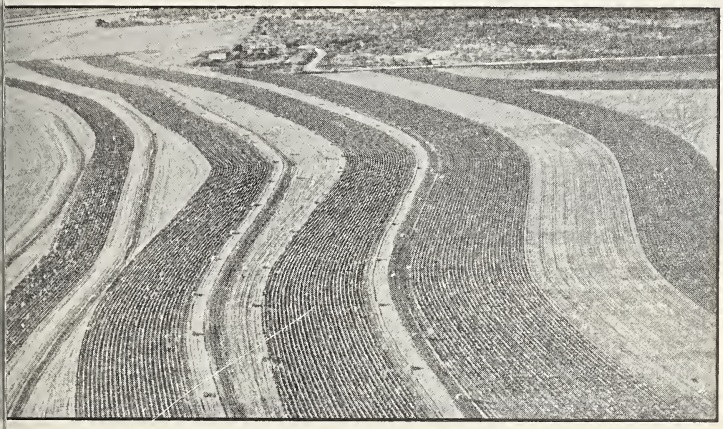


FIGURE 76. PREVENTION OF EROSION BY TERRACING
(*Courtesy of Soil Conservation Service*)

FIGURE 77. SOIL EROSION
(*Courtesy of Soil Conservation Service*)

FIGURE 78. ROAD CUT IN LOESS, NATIONAL MILITARY RESERVATION, VICKSBURG, MISSISSIPPI
(*Courtesy of U.S. Geological Survey*)

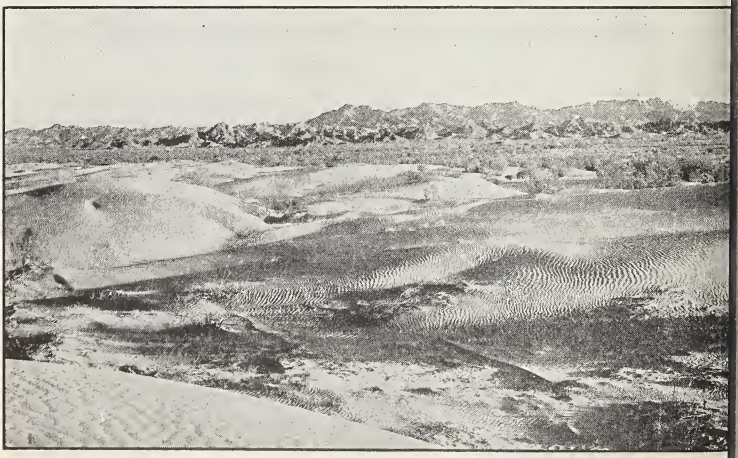


FIGURE 79. EASTERN EDGE OF SAND DUNE AREA NEAR MAMMOTH STATION, IMPERIAL COUNTY, CALIFORNIA
(*Courtesy of U.S. Geological Survey*)

e Missouri and Mississippi Valleys. The Chinese deposits of loess are veral hundred feet thick and constitute the best soil of China.

Another transportational effect of wind is the migration of hills of sand, own as *dunes*. The force of the wind pushes the particles of sand and rries them a short distance. The process is repeated, and in due time the tire dune will migrate. The growth of a dune begins with an obstacle ch as a brush or a stone which breaks the force of the wind; in time a ap of sand grains accumulates and continues to grow. Dunes form usu- y on shores where there is abundance of sand and wind blowing inland. ne Indiana dunes from Gary to Michigan City along the coast of Lake ichigan offer an example of these conditions. The wind blows the sand rticles in successive layers so that they are deposited parallel to its sur- ce. As the sand grains are blown over the crest, the windward side be- mes less steep than the lee side. The surface of the dune is covered with lges similar to ripple marks. As the dune migrates, it buries trees and her vegetation in its path. The invasion of fertile regions by dunes, erefore, requires checking by man. Dunes generally vary in height up a hundred feet, but under rare conditions, as in Africa, they may attain height of even five hundred feet.

SUMMARY

. The rocks of the earth undergo slow but definite changes.
. Rocks are aggregates of minerals. Minerals are naturally occurring compounds of the ninety-two elements.
. Elements combine with each other in constant ratios to form compounds.
. Ten elements comprise 99 per cent of the outer part of the lithosphere.
. The most common minerals found in rocks are quartz, feldspars, and ferromagnesians.
. Rocks are classified according to their mode of formation into igneous, sedimentary, and metamorphic.
. Rocks undergo weathering, or disintegration and decomposition through the combined effect of temperature changes and the chemical action of the gases in the atmosphere.
. Soil is one of the end products of weathering.
. Unwise cultivation aids in the erosion and depletion of soil. Measures can be taken to conserve soil.
. Wind transports particles of sand and dust, and thus forms sand dunes and loess deposits.

STUDY EXERCISES

.. Define the following terms: rock, mantle, soil, loess, dunes, schist, erosion, mineral, element, compound.

2. Make a table of the principal igneous, sedimentary, and metamorphic rock using the following form:

Name of Rock	Chief Minerals in Rock	Chief Characteristics: Texture, Appearance, Mode of Formation

3. What is the distinction between rocks and minerals? Why are most roc called silicates?

4. Name the igneous rocks described here which are formed at great depths, and give the equivalent rock formation at shallow depth.
   a) Light in color, contains excess of quartz and little ferromagnesian. .....
   b) Dark in color, contains excess of ferromagnesian minerals. .....
   c) Intermediate composition. .....

5. Name the sedimentary rocks described here and give their metamorph equivalents.
   a) Formed by consolidation of sand particles. .....
   b) Formed from shells of marine animals. .....
   c) Formed from extremely fine particles of clay. .....
   d) Formed from buried vegetable material. .....
   e) Formed from consolidation of coarse particles such as pebbles. .....

6. Give the three characteristics of metamorphic rocks by which they may identified.

7. Summarize the erosional and depositional work of atmospheric agents in chart as follows:

	Effect on Rocks	Erosional Land Forms Produced	Depositional Land Forms Produced
Wind			
Water vapor			
Oxygen and carbon dioxide			
Heat and cold			

8. Briefly discuss: (*a*) soil — its nature and mode of formation, (*b*) the impo tance of soil to the American community, (*c*) causes of soil erosion, (*d*) mea ures for checking soil erosion.

. Mark "I" if the material is an igneous rock; "S" if it is sedimentary rock; "M" if it is a metamorphic rock; "F" if it is a feldspar; "FM" if it is ferromagnesian mineral, and "N" if it is none of these.

....granite	....asbestos	....basalt
....limestone	....quartz	....gabbro
....schist	....sandstone	....gneiss
....marble	....bituminous coal	....quartzite
....conglomerate	....andesite	....rhyolite
....shale	....anthracite	....diorite
....slate	....orthoclase	

. How is soil formed? What is the difference between poor and good soil?

. Describe briefly how you would determine

(*a*) whether certain igneous rocks were formed near the surface or at great depth.

(*b*) whether a certain lava flow consists of basalt or rhyolite.

FOR FURTHER READING

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An excellent book for the general student who desires extensive reading on geology. The arrangement and treatment of subject matter although scientific are for the student who will not specialize in science. Chapters 1, 2, and 3 give an introduction to geology. The discussion of rocks and minerals will be found in Chapters 3 and 5.

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An excellent introduction to chemistry for the layman. A discussion of the elements will be found in Chapter 1.

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A book primarily designed for the general student. Chapters 1–4 will be found of aid by the student who has had no previous acquaintance with the study of matter.

. Briscoe, Herman T., *College Chemistry.* Boston: Houghton Mifflin Company, 1945.

A college textbook on chemistry. A discussion of mixtures, compounds, and elements will be found in Chapter 1.

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A college textbook on chemistry. A discussion of elements, compounds, and mixtures will be found in Chapter 2.

8

The Waters Wear the Stones

IN THE PRECEDING CHAPTERS a close look at the earth showed that a nu ber of changes, operating on a large scale, are constantly changing its fa The changes of the atmosphere as they affect man and the rocks were d cussed somewhat in detail. The rocks of lofty mountains, considered fi and solid, were shown to be slowly crumbling to fragments. It is appare that vast changes are occurring over the face of the earth; the tendency the changes studied thus far is towards reducing the higher portion of t earth. In this and following chapters it will be shown that the face of t earth is undergoing a cycle of changes. These changes may be grouped a cording to the general tendency of the processes as follows:

(1) *Gradation:* the processes which tend to bring the surface of the ea to a common level. The action of the atmosphere in this direction h already been considered. Changes in a similar direction are effected by t movements of ground water, running water, glacial ice, and the s Through continuous erosion by these agents, the higher portions of t earth's crust are worn away or degraded; the process is called *degradati* On the other hand, the material worn away is deposited in the lower pa of the crust of the earth, such as low land, lakes, or oceans. This buildi up process is called *aggradation.*

(2) *Diastrophism:* the changes occurring from the various movements one part of the lithosphere with respect to another. These changes a responsible for the continuous elevation of the land.

(3) *Volcanism:* the changes resulting from the movements of the molt rock masses.

All these processes may be grouped into a cycle of changes, one ser having a tendency to degrade and wear away the continents, while the oth tends to build up the continental masses. Thus, as a parallel to the cy of the seasons and that of plant and animal life, we find a cycle of geologi changes constantly in operation affecting dead matter.

GROUND WATER

The water that is discharged by the clouds in the form of rain always eks a lower level, and eventually finds its way back into the ocean. After ch rainfall, part of the water runs off into streams; some is re-evaporated, ıile another part, referred to as ground or subsurface water, sinks into the rth. Thus the mantle rock and bed rock down to a certain depth con- in considerable amounts of water. The amount of ground water has en estimated to be sufficient to submerge all the continents one hundred :t deep. This figure is only approximate, but it indicates the extent of e circulation of the hydrosphere within the outer part of the lithosphere. ıe amount of water in various rocks depends on their porosity or open aces left in the arrangement of mineral particles. The open space be- 'een particles varies from 1 per cent, as in compact, crystalline rock, to per cent in very porous sandstone. As the water descends, it finally aches a point where all mantle rock or bed rock is saturated with water, d this internal surface, or interface, is known as the *water table.* The ter table tends to follow the general contour of the land and generally es after heavy rainfalls. Ground water first descends until it reaches the ter table, and from there it follows the general direction of run-off water the surface. The movement of ground water is very slow. It may vary m a few feet to a few hundred feet per year and depends primarily on e escape of water in the underlying rocks. This flow follows the path of st resistance, usually along cracks and fissures, to emerge at lower rels.

ergence of Ground Water

When the water table intersects the surface of the land, water emerges seepage or *springs*, usually in a hillside or valley. Springs also form at e base of pervious rock, such as sandstone; with less pervious rock, such shale, underground openings are important in many regions as sources of ter supply. In regions where springs are not found, wells are bored into e ground to a point below the water table. The bottom of the well should

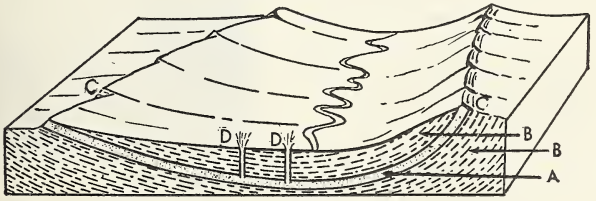


FIGURE 80. CONDITIONS FOR ARTESIAN WELLS

l denotes the aquifer; B, layers of rock; C, outcropping of aquifer; D, Artesian wells

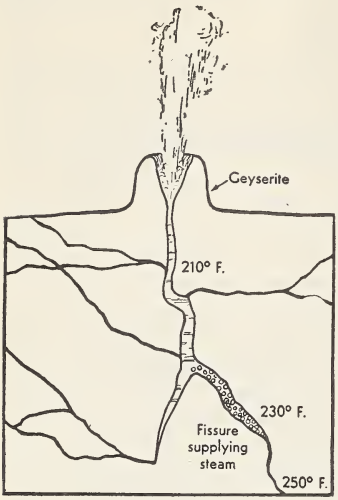


FIGURE 81.
CONDITIONS FOR GEYSERS

Water emerging from springs in certain localities is hot, ranging in temperature from 100° to 200° F. The hot springs in Arkansas and in Yellowstone Park are among the best known *thermal* (or hot) springs in this country. In such regions there are masses of hot rock which come in contact with the ground water, thus heating it before it emerges at the surface. In the Yellowstone region certain hot springs become turbulent and at regular intervals throw a jet of water and steam up in the air, and then subside for periods ranging from minutes to hours. Such springs are called *geysers*.

The condition necessary for a geyser is essentially a hot spring having an irregular tube. The irregular geyser tube extends downward nearly vertically into a region of hot rock. The tube is filled with water from the

be in a permeable rock, in order tha it may replenish itself rapidly. Dee wells from which ground water rise in a continuous flow to the surface ar called *artesian wells*. The condition for artesian wells are illustrated i Figure 80. A porous layer such a sandstone (*A*) lies between impervio rocks such as shale (*B*) which are in clined, and water may enter at th outcrops of the sandstone (*C*). Th water moves along the sandstor slowly, which thus forms a water co ductor, or *aquifer*, of an artesian wel If a hole is bored at some point (*D* water will rise to the surface owing t the difference in elevation between (C and (*D*).

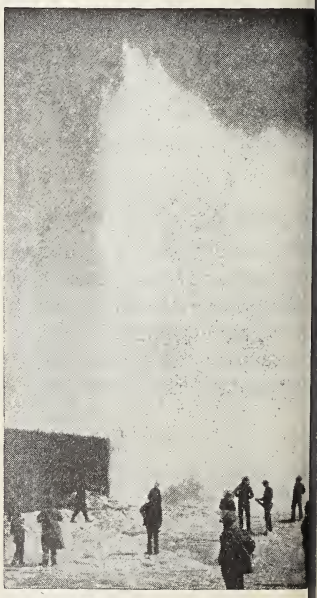


FIGURE 82. ERUPTION OF OLD FAITHFUL GEYSER
Yellowstone National Park
(Courtesy of U.S. Geological Surve

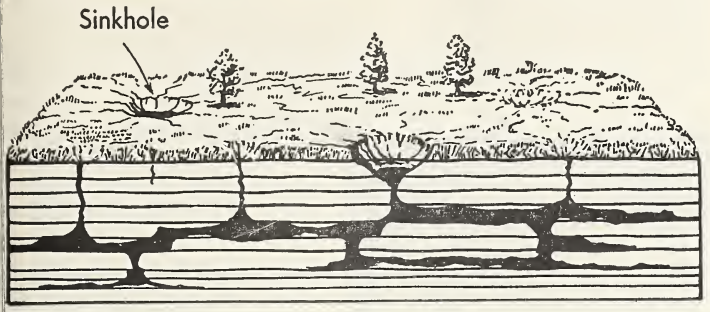


FIGURE 83. SOLVENT ACTION OF GROUND WATER
Subsurface water forms caverns in limestone

rounding rocks. The water in the lower part of the tube is heated above ?° F., but does not become steam, because of the pressure of the column water above. Finally, the temperature rises to such a point (about 250° that steam is formed, even under the great pressure. This pushes up column of water, and some of it spills over at the top and thus reduces pressure. A part of the superheated water flashes into steam and an ption follows.

Solvent action of ground water. In falling to the earth, rain absorbs car- dioxide, oxygen, and other gases. Organic acids are added to it as it sses through the soil, and increase its solvent power. As it seeps through rocks, it is heated, and its solvent power is further increased. There- e, as it circulates through the rocks, it dissolves the most soluble min- ls, increasing the porosity, and eventually produces a crumbling effect. r example, the cementing material in many sandstones is calcium car- nate, which is slightly soluble in water charged with carbon dioxide; ter passing through outcrops of sandstones causes the rock to break into se sand. A part of the dissolved mineral matter is deposited elsewhere, l another part is discharged into streams and is ultimately carried to the . Some of the dissolved minerals are deposited in the seas or lakes, and more soluble salts accumulate through the constant evaporation of ter and give the characteristic salinity to sea water.

The solvent effect of ground water on limestones has produced *caves*, *kholes*, and *natural bridges*. The water passing through cracks enlarges m, in time producing channels, tunnels, and chambers which, when con- ted with the surface, are called caves. A number of remarkable caves known in the United States. The Mammoth Cave is in the limestone in of the Ohio River in Kentucky. In this case there are several hun- d miles of galleries and passageways connected with chambers, lakes, ers, and waterfalls.

Deposition by Ground Water

Water as it circulates deposits or precipitates part of the mineral matte that it carries. Thus it may deposit calcium carbonate or silicon dioxid in the cracks of rocks. Water in contact with igneous rocks carries awa some of the metallic compound they contain and deposits ther in cracks or fissures. Such de posits are known as *mineral vei* deposits. The majority of th metals, including lead, zinc, an copper, are extracted from com pounds which are obtained fro vein deposits.

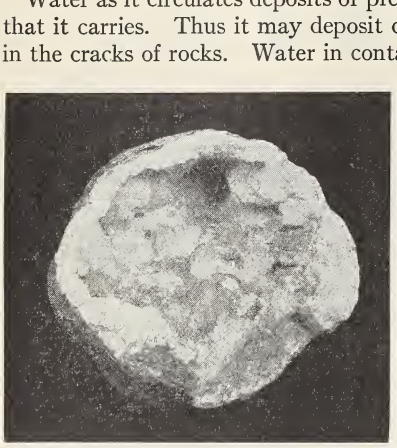


FIGURE 84. A GEODE

The deposition by ground wate around some nucleus, such as small object like an insect or mineral particle, gives rise t rounded irregular bodies calle *concretions*. Sometimes cavitie are filled with crystal deposit usually of quartz or calcite and pointing inward. Such forms, calle *geodes*, occur in many rocks; often they are found as large pebbles whic when broken disclose the cavity with well-defined crystals. The be known examples of deposition by water are formations of *stalactites* an *stalagmites* in caves. When water containing carbon dioxide passes dow ward through a limestone formation, it dissolves a quantity of calciu carbonate as calcium bicarbonate. On reaching the roof of the cave, som of the water evaporates and gives up some of its carbon dioxide, with th result that part of the calcium carbonate is deposited; when the drops water fall to the floor more calcium carbonate is deposited by the sam process. As a result, long icicle-shaped stalactites extend vertically dow ward from the roof of the cave, and similar, but usually thicker, stalagmit extend vertically upward from the floor.

Occasionally ground water deposition becomes an exchange of matte in that one substance may be dissolved and an equal amount of anoth deposited. Such an exchange is known as *replacement*. By this proces buried trunks of trees and bones of animals often become slowly petrifie The organic material is dissolved and simultaneously a mineral, usual silica or calcite is deposited. The petrified forests of Arizona and Yello stone Park and the petrified bones of dinosaurs are examples of replac ment. Thus, by solution and redeposition, ground water exerts a met morphic effect upon the rocks.

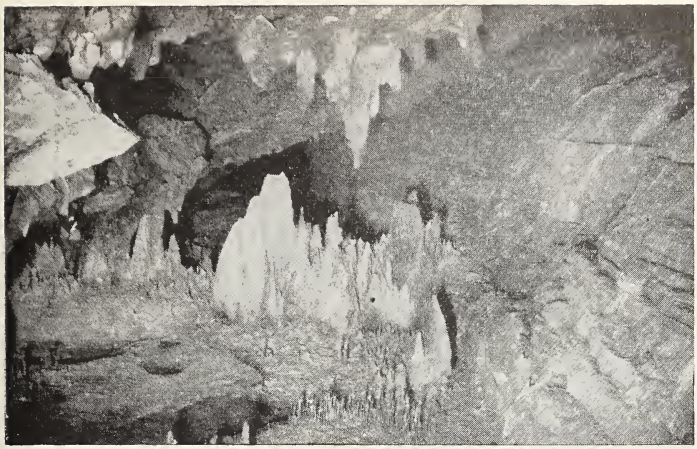


FIGURE 85. STALACTITES AND STALAGMITES
Great Onyx Cave, Kentucky. (*Courtesy of U.S. Geological Survey*)

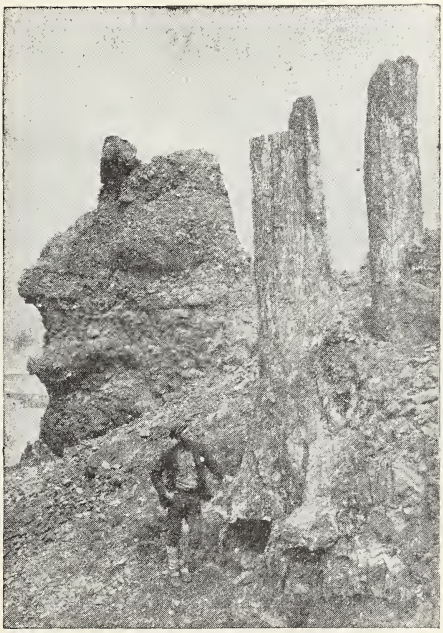


FIGURE 86. PETRIFIED TREE TRUNKS
Yellowstone National Park. (*Courtesy of U.S. Geological Survey*)

RUNNING WATER

Stream Erosion

By far the most important agent operating to modify the shape of the earth is running water. The processes of erosion and deposition by the many streams, whether small or large, that we see everywhere, occur on a grander scale and work faster than the other processes of erosion that have been studied. It is running water that sculptures the land, wears away the hills and mountains, and transports the eroded material to be deposited at lower levels in the form of flood plains and deltas. This can be realized when one travels over any extensive region where there are ravines and valleys, small brooks, larger streams and rivers, broad plains, waterfalls, and rapids, all indicating the constant activity and force of this agent of erosion. A certain amount of erosion is produced by rainfall when water collects as a sheet and moves over the surface of the ground. Usually during rainfall the water collects in small depressions in the ground, forming *rills*, which in turn unite in larger depressions forming *rivulets*, these in turn forming *streams*. Thus there are along hills small depressions at the sides which are called *gullies*, and larger depressions at the base which are called *ravines;* the ravines finally empty into the main channel or stream which runs through the valley. Each depression, large or small, has its tributaries, and the whole river system is much like a tree, the trunk emptying into the sea with its branches, twigs, and leaves extending inland. The whole system is engaged in erosion and pushes upwards, lengthening its course in a headward direction. The process is slow if measured in terms of human generations; nevertheless, the evidence is convincing. Continuously the material of the upland is washed away, the ridges and hills are lowered, and the final result is a featureless level surface, called a *peneplain* (almost a plain). In time, the region may be uplifted again, and thus the cycle of erosion may begin anew.

Generalized Cycle of Stream Erosion

By continued enlargement a gully grows into a ravine and eventually into a valley. At first the stream is intermittent, but as erosion deepens the valley eventually the deeper parts reach the water table, thus obtaining a steady supply of water and forming a permanent stream. The stream valley goes through a series of changes which, for the purpose of characterization as to its stage of development, are classified as *young*, *mature*, and *old*. However, valleys may also be developed by the outflow of a lake or in the uplifting of mountains by the downwarping of parallel folds (see page 180).

In early youth the upland is dominant in the topography of the region. The surface features are due mostly to causes not related to stream er

FIGURE 87. FORMATION OF RILLS BY RUNNING WATER
(*Courtesy of U.S. Department of Agriculture*)

FIGURE 88. RILLS ENLARGE INTO GULLIES BY HEADWARD EROSION
(*Courtesy of U.S. Department of Agriculture*)

FIGURE 89. A SLOPE TENDS TO INCREASE THE SIZE OF GULLIES
(*Courtesy of U.S. Department of Agriculture*)

FIGURE 90. A SLOPE WITH NUMEROUS GULLIES
Scott's Bluff, Nebraska. (*Courtesy of U.S. Department of Agriculture*)

sion, such as elevation of a portion of the sea floor, vulcanism, continental glaciation, or the draining of a lake. The divides between the valleys are generally broad with few tributaries, and the region is imperfectly drained. The stream channel occupies practically all of the valley floor, the banks rising directly on each side of the channel; the banks may be high or low, steep or gentle, according to the hardness of the rock, relief and climate. The cross profile of most young valleys is V-shaped. The dominant type of stream erosion during early youth is downcutting. Since the gradient is steep, swift rapids and falls may develop along the crooked courses of the youthful streams. The canyons of the Colorado and Yellowstone are examples of youthful regions and stream valleys on a large scale. As erosion proceeds the tributaries become more numerous, the broad divides change into narrow ridges and the valley passes to a stage of maturity.

In early maturity, the region, full of slopes, presents a rugged appearance; since a complete network of drainage has been developed, the region is almost perfectly drained. As the tributaries develop, the broad divides are dissected into narrow and irregular ridges, then into short hills and spurs. The main stream channels do not occupy all the valley floor but are bounded on one or both banks by a level flood plain of small or great width. The development of the flood plain is mainly due to the decrease in gradient and consequent decrease in downcutting. As the erosion of the stream is directed towards the sides of the valley, the stream begins to meander from one bank to the other so that steep bluffs occur on both banks. With increasing maturity, the flood plain becomes broader and the profile of the valley sides assumes the shape of sweeping curves.

As the remaining uplands are eroded by the tributaries, there is a gradual decrease in the height of the hills and the region is reduced to a featureless plain near the level of the streams. As the flood plain develops broader and broader, the stream channel is confined wholly within it, though its course may meander. The higher portions of the plain which follow the stream banks are called *natural levees* (see page 161). The plain is imperfectly drained and may develop marshes or lakes, frequently of the crescent (oxbow) type. It will be recalled that this type of land surface, a gentle undulatory surface of low relief, is called a *peneplain.* When the peneplain approaches the level of the sea, it is said to be near the base level, which is the lowest possible level to which any region may be eroded. It should be clear, however, that a particular region may be a peneplain and still be very far above base level.

The cycle of erosion described is summarized in Table 16. It should be understood that the cycle is a hypothetical one for humid regions and that it may be altered by climate and other factors and interrupted at any stage by geological forces which otherwise change the region. For instance, crustal movements may increase the gradient of an old region, thus

FIGURE 91. CANYON OF THE YELLOWSTONE RIVER

Showing typical V-shaped profile of a youthful valley. (*Courtesy of U.S. Geological Survey*)

FIGURE 92. ENTRENCHED MEANDERS OF SAN JUAN RIVER, UTAH
(*Courtesy of U.S. Geological Survey*)

rejuvenating the stream. The rejuvenated stream has inherited a meandering course from an earlier erosion cycle but has again deepened its valley, redeveloping a V-shaped cross profile; this winding V-shaped stream is said to exhibit *entrenched meanders*, and may be bordered by terraces, remnants of an old flood plain. The meanderings of the Susquehanna River in northern Pennsylvania and southern New York afford an example of entrenched meanders. Many rivers through mountainous regions, such as the Susquehanna, have kept their courses during the elevation of mountains, and their banks are often used by man as routes of travel. Deposition of glacial débris and flow of lava may also interrupt the course of a stream or the cycle of erosion in a particular region. Many submerged river valleys covered by glacial drift are found in Illinois.

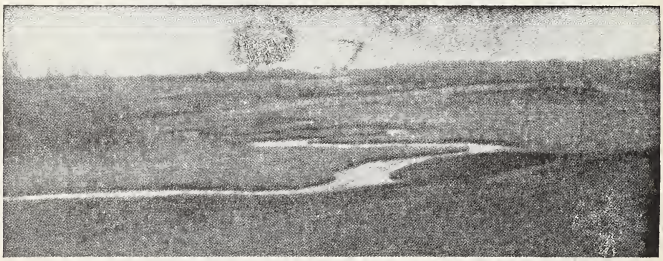


FIGURE 93. A MEANDERING STREAM IN AN OLD VALLEY
(*Courtesy of Illinois State Geological Survey*)

TABLE 16. SUMMARY OF STREAM EROSION CYCLE

Characteristics	Youth	Maturity	Old Age
Stream valleys			
Shape	Mostly V-shaped with steep walls; channel occupies all valley floor	Broad with flaring sides; channel does not occupy all valley floor; development of flood plain	Gentle slopes with broad flood plain meandering channel bounded by low plains.
Type of Erosion	Mostly downward; high gradient	Lateral; gradient diminished	Valley widening, ending in a peneplain
Regions			
Drainage	Imperfect	Nearly perfect	Imperfect
General features	Broad divides; few and short tributaries; falls and rapids	Narrow divides; numerous and well-developed tributaries; flood plain begins.	Trend towards featureless plain; few tributaries with broad flat floors

Transitory Features

As the river system develops, a number of features, such as falls and rapids, may arise, which, though they may be transitory as far as geological time is concerned, are regarded as permanent by most humans encountering them. Whenever a stream flows from harder to softer beds of rock there is differential erosion: the softer beds are cut away at a faster rate than the more resistant ones farther upstream, and thus there will develop a series of *rapids*. As the erosion proceeds, the rapids become steeper and finally a waterfall may result. Waterfalls may be also formed by other geological conditions. For example, a glaciated valley is deepened more than the valleys of the tributary streams, and after glaciation, falls develop at the junction. In the same manner, falls may develop at the junction of tributary streams if the main valley is eroded at a faster rate.

The falls at Niagara have been formed by the recession of horizontal beds of unequal hardness. The bedrock at the falls is of dolomitic limestone, about eighty feet in thickness, with weaker shales and sandstones underneath. The softer beds are eroded more rapidly, leaving the harder capping limestone projecting outward over which the water plunges. The process of undercutting is accelerated by the spray of the falling waters until the weakened projecting shelf breaks away in blocks and falls below. In this manner there is a constant recession of the falls, which has been measured quite accurately for the past hundred and fifty years. According to the figures, the recession amounts to three feet per year. By this type of recession, Niagara Falls has moved back seven miles, forming a gorge of that length. The width of Niagara Falls is a thousand feet and that of the adjacent Canadian Horseshoe Falls is three thousand feet. The total amount of water falling per second is ten thousand tons, with 94 per cent going over the Horseshoe Falls.

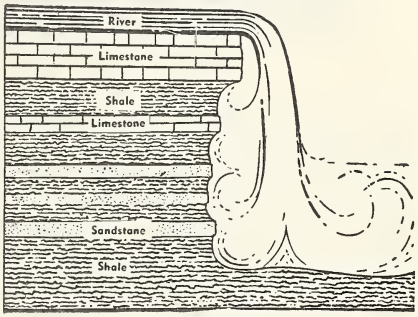


FIGURE 94.
SECTION OF HORSESHOE FALLS, NIAGARA, SHOWING STRUCTURE AND STRATA
(*After Gilbert, U.S. Geological Survey*)

Stream Erosion and Transportation

As noted previously, a stream is constantly at work eroding the land. The process of erosion is accomplished by the solvent action of water on the

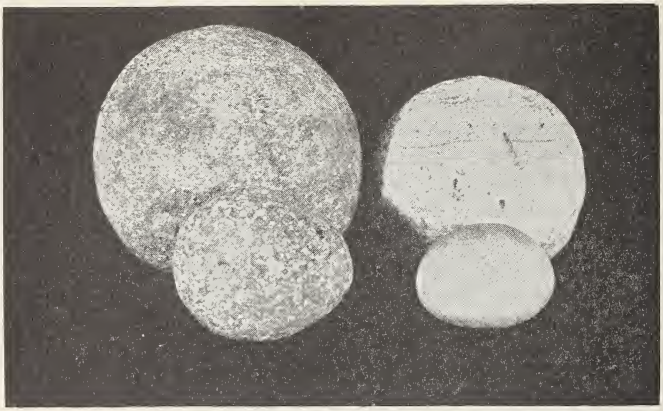


FIGURE 95. TOOLS OF THE STREAM
Rounded pebbles from the bed of a dry stream

rock and by the ability of the moving liquid to pick up and carry away silt, sand, pebbles, and even rocks. The solvent action, though not noticeable, is measurable, as can be shown by evaporating a definite amount of filtered water obtained from a stream. As the run-off water flows through gullies, ravines, and valleys it picks up weathered earth and rock material and through these exerts a constant grinding friction against the rock of the floor and the sides. The sand grains, pebbles, and rocks driven by the force of the moving water scrape and scour the bed of the stream and thus excavate or widen the stream channel. The erosive power of the stream depends on a number of factors, but primarily on the velocity and volume of water.

The velocity is determined to a great extent by the gradient or slope of the stream bed and its shape. The greater the slope, the greater the velocity and consequently the greater the abrasive action. If the velocity be doubled, the abrasive power is increased at least four times. This becomes apparent if we consider that in doubling the velocity we double the number of particle bombardments against the rock per unit time and also double the force of such bombardment. Therefore, the abrasive power usually varies between the square and sixth power of the velocity.

The volume of water in streams varies with the rainfall. In the spring when snow melts in the mountainous regions, and after heavy rainfalls many moderate streams become raging torrents with destructive power. The increased volume of water not only increases the transporting capacity of the stream, but also the velocity of the water, since the friction of the upper layers of water is less than that which flows against the bed rock.

FIGURE 96. EROSION IN A RIVER BANK
Turkey Run State Park, Indiana

Thus, the velocity and the volume of water determine the transporting power of the stream.

The mode of transportation of the stream load can be observed by watching the flow of water near the bank of a rapid stream. The fine, lighter particles may be carried in suspension without a great tendency to settle to the bottom. The heavier particles of sand and the pebbles are rolled and dragged along the bed of the stream. Since the bed is seldom uniform, the sediment is carried along jerkily; the boulders and heavy pebbles cause a deflection of the moving water, producing eddies and upward currents. As they tend to reach the bottom of the stream, the particles are picked up and carried forward, or they may fall to the bottom and remain there until they are dragged, rolled, or thrown upward again.

The erosive power of streams may be visualized by considering the load that the Mississippi carries to the sea. It has been estimated that this river discharges annually into the Gulf of Mexico 2×10^{13} cubic feet of water, containing about a hundred and fifty million tons of material in solution and four hundred million tons in suspension. Since the Mississippi river system drains an area of about 1,200,000 miles, the basin is reduced by one foot every eight thousand years. If we take this as an average rate of erosion (*denudation*) for all the rivers of the United States and also consider that the average elevation is two thousand feet, we find that it will take sixteen to eighteen million years, more or less, to reduce the land to sea level, if no crustal movement intervenes. Though this rate may seem slow, it is regarded as rapid from a geological standpoint.

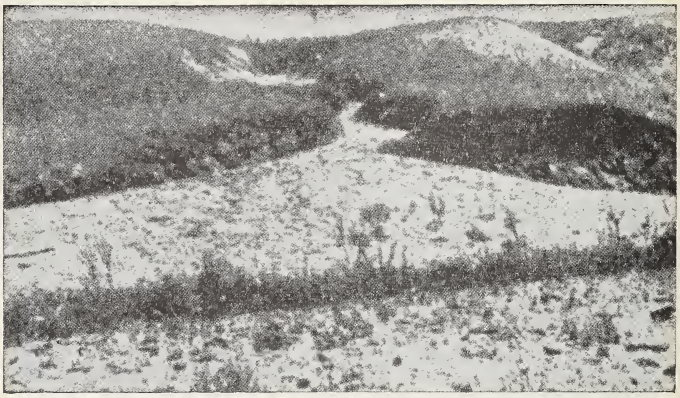


FIGURE 97. A SMALL ALLUVIAL FAN
Radiating from the base of the mountain
(Courtesy of Illinois State Geological Survey)

Stream Deposition

When the velocity or the volume of a stream is diminished, a correspond-ing diminution of transporting power occurs, and therefore a part of the load is deposited. This happens many times in the life of a stream, and the resulting river sediment is called *alluvial deposits* or *alluvium.* Such sedi-ments accumulate usually at the foot of hills and mountains, and in stream channels and flood plains.

When the velocity of the stream is checked or slackened as a result of a decrease in gradient, as when a stream flows from a mountain into a plain, a part of its load is dropped in the form of an alluvial fan-shaped deposit. As the sediment accumulates, the fan radiates outward from the mouth of the stream and is much thicker close to the place where the velocity is first checked. Huge fans have been built at the base of mountains with steep slopes.

During high water, a stream may overflow its banks and deposit silt, sand, and mud on the flood plain over which it runs. As the river widens its valley and ranges laterally in greater and greater curves, it deposits material along the inside of the curves and erodes the land on the outside, with the eventual result that flood plains are built on both sides of the stream. The Mississippi has built a flood plain starting from Cairo, Illinois, where it meets the Ohio River, to the Gulf of Mexico. This flood plain is about six hundred miles long, forty to sixty miles wide, and twelve thousand square miles in area.

As the flood plain becomes higher on either side of the stream, deposition occurs during highwater mark along the sides of the channel where the

elocity of the water is checked. In this manner, the flood plain develops idgelike deposits at the border of the stream, which are known as *natural ees* and which offer some protection from seasonal floods.

Another type of alluvial deposit occurs at the mouths of streams as they nter the sea or a lake. The velocity is checked and the load drops to the ottom, gradually building successive layers of alluvial fans which grow to

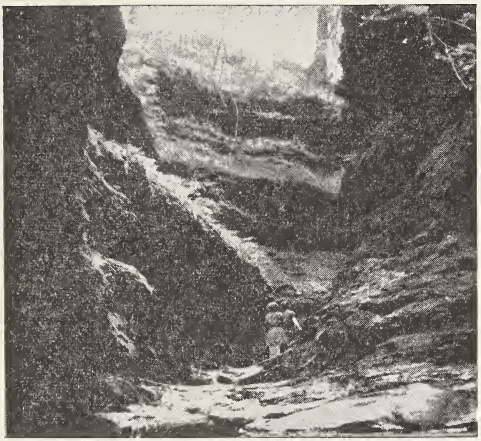


FIGURE 98. A SMALL CANYON ERODED BY A STREAM OUT OF SANDSTONE
Turkey Run State Park, Indiana

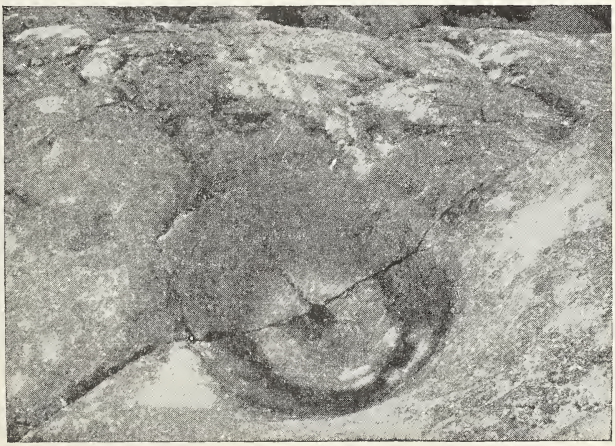


FIGURE 99. A POT-HOLE IN THE BED OF A STREAM

a shape resembling an inverted Greek letter Δ, and hence are called *deltas*. The stream eventually is divided into many channels across the delta, and through these it continues to build new alluvial deposits farther out in the sea.

Deposition of alluvium is important to man. Mention has already been made of the fact that two of the oldest civilizations grew up along the river banks of the Nile and the land enclosed by the Tigris and Euphrates. The reasons are not hard to find. The land that is a mile or two away from the banks of the Nile is a desolate desert. Yet in a small strip of land on either side of the Nile there exists even today the most dense population of the world. The land can support that population, thanks to its fertility, for the river brings from equatorial Africa a deposit which is extremely fertile. Long systems of canals irrigate and flood the land, so that it is possible under the subtropical sun to raise three or four crops a year. The river system with its valleys, tributaries, and flood plains has been the cradle of mankind.

SNOW AND ICE

The weathering effects of freezing water were considered in the preceding chapter. There is a constant wedging action on the mantle rock and the outcropping bed rock. Similarly, when the rivers freeze, a wedging action at the sides and bottom occurs. When the ice begins to melt in the spring many boulders encased in ice float downstream. However, the erosional and transportational effects of ice in frozen rivers or lake shores are not as significant as those resulting from large masses of ice in motion. Huge moving ice masses, called *glaciers*, are the chief agents of erosion in high mountains and in the Arctic zones, as in Alaska and Greenland. There is abundant proof that much of the present topography of Illinois, Wisconsin, and the Northwest is due to large glaciers that flowed several times over these regions in the past.

Formation of Glaciers

In high altitudes snow remains the year round. The snow line in the Alps is about eighty-five hundred feet above sea level; in Alaska it is five thousand feet; in Greenland two thousand feet. When snow falls, it is flaky and dry, but when it accumulates, it becomes compact. Under the effect of pressure of the layers above, each snowflake partially melts and refreezes, acquiring a granular texture like small particles of hail. In time by successive changes, snow many hundreds of feet thick is finally converted into compact ice by its own weight.

When the ice attains a great thickness and the slope is steep enough, it begins to spread outward and downward. If the gradient is not steep and the land is fairly horizontal, vertical pressure at the center spreads the ice

FIGURE 100. A VALLEY GLACIER
Tanana Glacier, Alaska. (*Courtesy of U.S. Geological Survey*)

FIGURE 101. SECTION OF FOOT OF VALDEZ GLACIER, ALASKA
Showing source of river and sub-glacial tunnel from which it emerged
(*Courtesy of U.S. Geological Survey*)

in all directions and makes an *ice cap* or *ice sheet.* Greenland is covered with such an ice sheet two hundred thousand square miles in area and eight thousand feet in thickness at the center. The Antarctic continent is buried under a larger ice cap, covering more than five million square miles. When the gradient is steep, as in the valleys of high mountains, the sheets of ice move downward and are called *valley glaciers.* Glaciers of this type are found in the Alps, Caucasus, and Himalayas. The most important in the United States are those of Mount Rainier in Washington.

Valley glaciers are usually one to two miles long, and move about one foot a day. The rate of motion — which in the winter is about half of the summer rate — is faster in the middle than at the sides or bottom since the friction against the valley walls and floor impedes motion. Because of these obstructions, tension develops which results in cracks that widen to form chasms called *crevasses.*.

Many theories have been proposed to account for glacial motion, of which only one will be briefly mentioned. It is assumed that under the great pressures from above and behind, the ice crystals at points of greatest compression melt and the water produced refreezes after undergoing a slight relative change in position. As the valley glaciers move downward there is melting and evaporation. The water flows into crevasses which may lead into subglacial channels. Ultimately the water from the melting of the glacier emerges in the form of streams or lakes beyond the ice. If the rate of melting exceeds the rate of supply of ice by snowfall at the head, the glacier recedes, and when the supply exceeds the melting, the glacier advances. Occasionally the two rates will approximate each other and the glacier appears to be stationary. When glaciers end in the sea as in Greenland and Antarctica, huge blocks of ice called *icebergs* break off and fall into the sea.

Glacial Erosion and Deposition

The glacier acquires a load of rock débris as it moves. Mantle rock falls from the valley sides or is plucked away from the cliffs and edges. This load, which is considerable, becomes the chief tool of glacial erosion. As the glacier moves, a part of the load, by constant grinding, is reduced to powder. The sides of the valley are scoured and ground out. In many places the grinding action produces scratches, grooves, and smooth surfaces. The boulders deposited by glaciers show similar polish and scratches, called *striae.*

Prolonged glacial action changes a youthful V-shaped valley into a U-shaped one, since the sides are eroded as rapidly as the bottom. In the glaciation of a valley that has tributaries, the main channel is eroded to a greater extent because of the greater volume of ice. When the ice recedes the tributary valley is left hanging high above the floor of the main valley and is hence known as a *hanging valley.* The Yosemite Valley has hanging

ributary valleys whose streams plunge eleven hundred feet down to the oor of the main valley. The plucking and shearing action of glacial ice roduces on the upper ends of practically all glaciated valleys amphi- neater-like shapes called *cirques*. In the high latitudes, glaciated valleys ıay be partially submerged by the sea to form depressions called *fiords*.

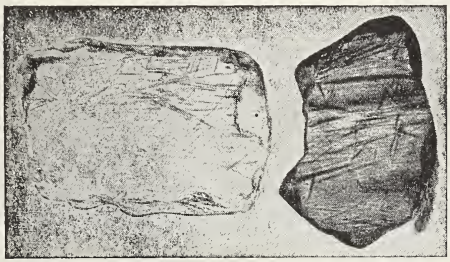


FIGURE 102. GLACIATED STONES SHOWING STRIAE
Sketches. (*Courtesy of Illinois State Geological Survey*)

FIGURE 103. GLACIAL POLISH ON FLAT ROCK
Near Baraboo, Wisconsin

When glaciers melt, a heterogeneous mass of rock débris, ranging fro clay to huge boulders, is deposited. The name applied to such deposits *glacial drift.* The material dropped directly by the glacier is known as *til* Material carried by the glacial stream and deposited farther along is know

FIGURE 104. YOSEMITE VALLEY

The glaciated U-shape is manifested throughout. To the right there is a hanging val with water falls. (*Courtesy of U.S. Geological Survey*)

FIGURE 105. TENAYA CANYON OF YOSEMITE VALLEY

A typical U-shaped glacial canyon. (*Courtesy of U.S. Geological Survey*)

glacio-fluvial deposit. Ridges of till deposited by glaciers at their sides at their ends are known as *moraines*.

As the glacier moves, it deposits irregular heaps of excess load which accumulate at its borders. When the ice melts, these irregular ridges, called *teral moraines*, are left at the sides. At the end of the glacier, where the elting may proceed for a long period at the same rate as the advance, con-

FIGURE 106. CIRQUES

Head of the west fork of Sheep Creek on the crest line of Uinta Range, Utah, showing an -age surface cut by glacial cirques. (*Courtesy of U.S. Geological Survey*)

FIGURE 107. A GLACIAL BOULDER

In a pasture east of Devil's Lake, Wisconsin

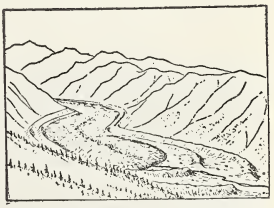


FIGURE 108. A GLACIER LEAVING A MORAINE

A sketch. (*Courtesy of U.S. Geological Survey*)

siderable till is dropped and forms ridges called *terminal moraines.* Ridge of this type may be deposited by material which is pushed by the front o the advancing glacier. These ridges may be quite high, but are not wid unless formed by great ice sheets, when they become as much as twenty miles in width.

Streams from melting glaciers carry considerable amounts of a flou like suspension of pulverized rock, sand, pebbles, and boulders, and d posit such glacio-fluvial material beyond the terminal moraines, in shap much like the alluvial fans. Many such fans may coalesce to develop a

FIGURE 109. TERMINAL MORAINE TOPOGRAPHY
(*Courtesy of Illinois State Geological Survey*)

FIGURE 110. ESKERS LEFT BY GLACIERS
(*Courtesy of Illinois State Geological Survey*)

itwash plain. Other characteristic deposits of glacial streams are winding dges of sand and gravel known as *eskers*, many of which resemble railway nbankments. These ridges are formed by subglacial streams or tunnels hich collect much of the water and débris carried down in the crevasses.

e Ages

In Illinois, Wisconsin, and other states, several layers of glacial drift e found separated from each other by thin deposits which indicate soil id vegetation of warm climates. From a study of these layers there are sumed to have been four different advances and retreats of the huge e sheets in recent geologic history. These are named the Nebraskan, ansan, Illinoian, and Wisconsin advances.

Study of glacial striae made in many parts of North America, of the ignment of moraines, and of other evidence, indicates that the ice origi- ited outside the Arctic regions, in three main centers. One originated in abrador on the coast of Hudson Bay, one west of Hudson Bay, and the ird in the Rocky Mountain area. From these three centers, ice sheets diated, covering most of the North American continent from the lower rt of Illinois northward. The extent of the huge ice sheets may be real- ed from the dimensions given for the Greenland ice sheet. It is esti- ated that the ice sheet at its maximum covered four million square miles the North American continent. In Europe similar ice sheets covered ost of the northern countries. This subject will be discussed again in hapter 48.

THE SEA

The term *sea* or *ocean* designates the body of water that occupies 72 r cent of the earth's surface in basin-like depressions. It is the ultimate servoir in the water cycle for the material eroded from continents. It so acts as a reservoir for a considerable amount of heat received from the n. The amount of heat absorbed by water is retained for far greater riods of time than that absorbed by rocks and the soil. Great currents om the equatorial zones move warm water to northern latitudes and make e climate milder. Similar effects, though to a smaller degree, are effected large lakes. The water during the summer months is heated, and dur- g the winter as the water on the surface reaches 39° F. or 4° C. it becomes avier and sinks, thus bringing warmer water to the surface. This in rn heats air passing over the surface and exerts an influence on the at- ospheric temperature of the surrounding regions. At the same time it is agent of both erosion and deposition.

The average depth of the sea was given in an earlier discussion as two and e-half miles. It should not be thought, however, that this depth is at- ined within a few hundred feet of the land. Evidence from soundings and her oceanographic measurements indicates that the sea basins have

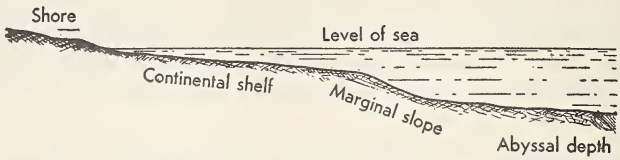


FIGURE 111. DIAGRAM OF THE SEA BOTTOM NEAR THE SHORE

overflowed and cover a considerable part of marginal land of the continent so that the first twenty to a hundred miles out in the sea are shallow, with depth seldom exceeding five hundred to six hundred feet. This shallo portion of the sea is really an inundated margin of the continent and called the *continental shelf*. It will be well to remember for purposes subsequent discussion that this shelf is not static, for many times in t past it has fallen below its present level and much of the present contine was inundated by shallow seas. As will be shown in the next chapter, ev now the various parts of the continental shelf are slowly undergoing elev tion or subsidence.

The continental shelf slopes gradually from the shore to a depth of abo six hundred feet, and then the depth increases rapidly to the average dep of the sea floor, which is two to three miles. Though the land is sculptur by deep valleys, hills, and ridges, according to our present knowledge t deep-sea floor is a vast flat expanse, broken here and there by a few mou tain volcanoes and depressions of great depth. The reason given for t lack of relief is that the sea floor is essentially an area of deposition, and t land an area of erosion.

Waves and Currents

Winds blowing over the surface of the sea keep it in constant agitati to a smaller or greater degree. In the relatively shallow waters of the c tinental shelf the formation of *waves* by winds is very common. Wa are formed by frictional action of the wind on the surface of the water a are pushed forward in rapid succession. As the waves approach shall water, their lower part drags on the bottom and is retarded, while the up portion is propelled forward with undiminished velocity. This produce shortening of the distance between crests (wave length) and an increase height of the crest and depth of the trough. Finally the crest rolls over a forms foamy *breakers*, dashing the water forward on the shore.

The force exerted by large waves may be enormous, so that erosion curs very rapidly. The south shore of Nantucket Island, which is expo to the waves of the Atlantic, has been known to retreat as much as six f a year. The pressure exerted by the dashing of waves of great hei against the cliffs may rise to two thousand or more pounds per square in

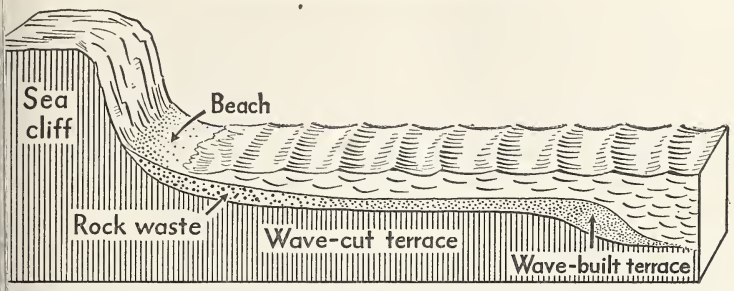
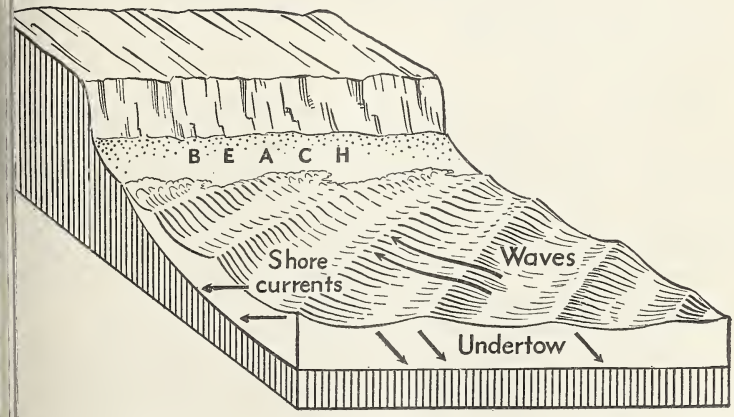


FIGURE 112. DIAGRAM OF THE EROSIONAL WORK OF WAVES

e sand, pebbles, and rock fragments carried by the water and hurled ainst the cliffs or shores exert a grinding effect and hasten the under- ting, thus producing sea cliffs with steep walls. The process is repeated, d the sea cliff is undermined and finally reduced to fragments at the base. this manner the cliff recedes, and the accumulated débris from the ded coastal land is dumped inward, forming a *wave-built terrace*. The rtion of land over which the sea has advanced is called the *wave-cut race*.

The water of the breaking wave which piles up on the shore returns to sea in the form of a current along the bottom and under the incoming ves. The return current, when it is perpendicular to the shore, is called *undertow*. When the water strikes the shore at an acute angle, the re- n current is roughly parallel to the shore, and is then called a *shore cur-*



URE 113. WAVES STRIKING AT AN ANGLE GIVE RISE TO SHORE CURRENTS

rent. These two currents carry away the material eroded by the action o the waves. The large fragments are moved back and forth until they ar ground to a sufficient degree of fineness to be moved seawards and de posited in deeper water. In this manner, shore currents carry fine materia and drop it at the entrance of bays where the water is deeper, formin ridges of deposited land called *spits.* The spit generally tends to close th bay, forming a *bar,* and thus simplifies the shoreline. Bars in certain place tie islands to the mainland; such bars are called *tombolos.*

Types of Shorelines

The topographic features of shorelines are closely related to the elevatio or lowering of the continental shelf. There are two general types recog nized as indicating whether there has been elevation or subsidence. Th first type, like that of the northeastern United States, is the shoreline o *submergence.* It is highly irregular, with many bays and promontories; occurs along coasts where the sea has encroached deep upon the land an has drowned valleys and formed deep bays and long headlands. There a depressed, or drowned, valley extending about a hundred and fifty mil beyond the present mouth of the Hudson River. In such shorelines th waves tend to cut headlands, and the shore currents to close the bays, so a ultimately to produce a straight shoreline. The other type of shoreline the shoreline of *emergence.* It occurs in areas where the continental she has been raised slightly above the water. This type is a flat coastal pla with numerous shallow lagoons and without any cliffs or rocks. In shoreline of this type the action of waves and shore currents has built a ditional bars and filled in the lagoons, thus again simplifying the shorelin In both cases, after the shoreline has been simplified, the erosional process cutting cliffs and building beaches and terraces continues as the cycle coastal erosion repeats itself.

Deposition in the Sea

Mention has often been made in this chapter that all material erod from the land, the muds, sands and gravels, ultimately are deposited sediments. A part of this disintegrated rock material is deposited on t flood plains of the valleys or in the bottom of lakes, and the rest is carri to the sea. Ultimately most of the eroded material, even if it is temporari deposited in the continents, reaches the sea. Thus, the sea is primarily basin of deposition. The material discharged into the sea by the strea and to a smaller degree detached from the land through the action of wav is of two kinds: material in solution and material in suspension.

The material in solution consists mostly of sodium, magnesium, and c cium compounds. Sodium chloride, or common table salt, makes up thr fourths of the dissolved matter, and the salty taste of sea water is d mainly to this compound. The bitterness is due chiefly to the magnesi

TABLE 17. MATERIAL DISSOLVED IN SEA WATER

Sodium chloride (salt)	77%
Magnesium compounds	16%
Calcium compounds (lime)	3%
Potassium compounds	2%
Traces of other substances — including gold and silver in minute traces	2%
	100%

mpounds. The amount of dissolved matter is 3.1 to 3.7 per cent by eight. If sufficient sea water were evaporated to obtain 100 g of solid aterial, its approximate composition would be as given in Table 17. In ldition, sea water contains dissolved gases such as oxygen and carbon oxide. From the dissolved material that is continuously brought to le sea, a part is precipitated by chemical reactions, and a large part of le calcium compounds is abstracted by shell-forming marine animals. s these organisms die their shells are deposited to form lime muds which ter form limestone. The lime-mud deposition takes place in shallow aters, where the lime-secreting organisms abound.

The material which is in suspension is dropped on the sea floor in the der of size of the particles. As the velocity of the water decreases, the rticles are sorted, gravel being dropped first, then sand, and then mud; le fine muds may be carried not only as far as the edge of the continental elf but even to distances from land as great as two hundred miles. This dicates that on the shallow continental shelf limestones, shales, and sand-one are being deposited to form sedimentary rocks. In this manner, it believed, most of the great deposits of sedimentary rocks found deep in le continents are formed. The sea is not stationary. Many times in le geologic past, parts of the continent were inundated by shallow seas to which streams emptied their loads, and organic life built up huge de-osits of limestone. The deep-sea deposits that have been brought up by oops and dredges show little evidence of material brought by the streams. hey have a slimy consistency and are known as *oozes*. Examinations dicate that these deep-sea slimy deposits consist of volcanic ash, shells simple types of plants and animals, and colloidal mud.

Man recognized rather early the changes brought about by the waters the earth, for he sang: "The waters wear the stones; thou washest away le things which grow out of the dust of the earth." [1] We may suppose lat he found a peculiar fascination in the bubbling brook and the flowing ver and drew similarities between his own life and the course of the ream. He saw himself in the noisy, bubbling, frothing youth going over taracts, then slowing down, and finally being quietly lost in the sea. He und also a peculiar fascination in the sea, though it was inhospitable and spired loneliness and fear. Very early in his speculations man recognized

[1] Job 14 : 19.

the importance of the changes brought about by the water of the earth and the water's kinship to life itself, for he assumed that water was th primordial element.

Detailed knowledge of the changes brought about by the moving water in their various forms, it is hoped, will increase the student's mental horizo and enhance his enjoyment of the beauty and orderliness of nature.

SUMMARY

1. The cycle of changes which occur over the face of the earth are: gradatio diastrophism, and volcanism.
2. Gradation includes the geological work of the atmosphere, ground wate running water, ice, and shore agents; these processes tend to bring the surfa of the earth to a common level.
3. Diastrophism includes the movements of the lithosphere and volcanism th movements of molten rock; these processes tend to build up land.
4. Ground water circulates very slowly and emerges to the surfaces to for springs, wells, and geysers.
5. Ground water by its solvent action on rocks and by deposition of dissolve mineral matter is instrumental in forming caves, sinkholes, natural bridge geodes, stalactites, stalagmites, mineral veins, concretions, and petrifi remains of plants and animals.
6. Running water is the greatest agent of erosion. Its erosional and depos tional work results in gullies, ravines, canyons, broad valleys, rapids, fal alluvial fans, flood plains, levees, and deltas.
7. Long-continued accumulation of snow gives rise to glacial ice.
8. Glacial ice by its erosional and depositional action gives rise to these top graphical features: moraines, glacial drift, eskers, glaciated valleys, hangi valleys, cirques, and fiords.
9. Erosional action of the waves and deposition by currents produce these top graphic features along the shores: cliffs, wave-cut terraces, wave-built te races, spits, and bars. The general tendency of shore agents is to simpli the shoreline.
10. The sea is a basin of deposition. Most of the large masses of sedimenta rocks found to day on the continents were deposited in the shallow seas whi in the past inundated the continents.

STUDY EXERCISES

1. The changes which are taking place over the face of the earth are group under the terms gradation, diatrophism, and volcanism. Explain the mea ing of each term and the direction of each process.
2. Draw a rough diagram serving to illustrate the conditions necessary for t formation of (*a*) a spring; (*b*) a well; (*c*) an artesian well; (*d*) a geyser Yellowstone Park; (*e*) petrification of a tree situated near a hot spring.

3. In the following list write "W" if the change has been produced by wind; "S" if by subsurface water; "R" if by running water; "A" if the change represents aggradation or deposition; and "E" if it represents erosional change.

.... loess	.... geodes	.... peneplain
.... dunes	.... alluvium	.... flood plain
.... deltas	.... stalactites	.... valleys
.... levees	.... pinnacles	.... springs
.... sinkholes	.... alluvial fan	.... caves
.... concretions		

4. Draw a rough diagram illustrating each of the following. Label all parts and give a brief statement below the diagram explaining the causes of changes depicted.

(*a*) The formation of a waterfall by water running through a bed of shale on top of which there is a thin cap (very thin layer) of limestone.

(*b*) The formation of a gully on a hillside unwisely cultivated.

(*c*) A glaciated young valley in which the glacier advanced up to the middle of the valley and then receded.

5. For each of these three types of valley give the numbers identifying its characteristics as listed below:

Young.....
Mature.....
Old.....

(1) distinctly U-shaped	(9) ox-bows
(2) very gentle	(10) V-shaped
(3) down-cutting	(11) many well-developed tributaries
(4) very wide flood plain	(12) beginning to form a flood plain
(5) levees	(13) steep gradient
(6) falls and rapids	(14) meandering
(7) steep-sided canyons	(15) carries fairly large rocks
(8) side-cutting	(16) few short tributaries

6. Mark "1" if produced by weathering or wind; "2," if produced by running water; "3," if produced by ground water; "4," if produced by glaciers; or "5," if produced by shore agents.

.... hanging valleys	.... exfoliation	.... loess
.... peneplain	.... soil	.... talus
.... falls	.... dunes	.... moraine
.... alluvial fan	.... eskers	.... striae
.... geysers	.... faceted stones	.... sorted deposit
.... rounded stones	.... terrace	.... chalk deposit
.... spit	.... bar	.... lagoon
.... cliff	.... flood plain	.... metallic deposit
.... polished rock	.... salt deposit	.... delta
.... stalactite	.... geode	.... fiord
.... levee	.... unsorted deposit	.... beach
.... canyon	.... cirque	.... cascade
.... sink holes		

7. Consult Table 16, giving the important characteristics of the various stages of stream erosion. For each stage explain the cause and conditions for each characteristic.
8. Give conditions for the following types of erosion or deposition:

a) levee	*f*) outwash plain	*k*) wave cut terrace
b) alluvial fan	*g*) valley glaciation	*l*) bar
c) delta	*h*) hanging valley	*m*) spit
d) lateral moraine	*i*) fiord	*n*) lagoon
e) terminal moraine	*j*) esker	

9. Give the characteristics of the two types of shorelines and the general trend in all shoreline changes.
10. Make a complete table summarizing all the work of gradational agents. Use the following form:

Gradational Agent	Erosional land form	Depositional land form

FOR FURTHER READING

1. Croneis, C., and W. C. Krumbein, *Down to Earth.*
The discussion of subsurface water and its geological action will be found in Chapter 9. Streams and valleys are discussed in Chapter 4, glaciers in Chapter 10, and shore agents in Chapter 12.
2. Longwell, C. R., A. Knopf, and R. F. Flint, *Outlines of Physical Geology*
The discussion of subsurface and running water will be found in Chapters 4 and 6. Glaciers are discussed in Chapter 8 and shore agents in Chapter 7.
3. Agar, W. M., R. F. Flint, and C. R. Longwell, *Geology from Original Sources.*
Excerpts from classic studies in geology pertaining to the work of subsurface water and glacial ice will be found in Chapter 4, similar references to streams and valleys in Chapter 3, and shore agents in Chapter 7. The story of a piece of chalk by Huxley in Chapter 7 is particularly recommended.

9

The Lofty Mountains

IE PICTURE of the face of the earth as given in the preceding chapters one of mobility and change. The pounding of waves on the shores, the wing of streams, the scouring of valleys by rivers of ice, the movements winds, were all studied as gradational forces tending to reduce the higher rtions of the earth. The logical end result of these changes would be ntinents with no hills, mountains, or plateaus. But opposing forces ting from within the earth tend to offset the work of gradation by build- g up land. *Diastrophism*, one of the most important of these forces, mprises all movements of the outer solid part of the earth, whether great small, rapid or slow. The old notion of *terra firma*, then, is meaningless, r the outer shell of the earth is unstable. Crustal movements may vary m those so slow as to be imperceptible to those which are rapid, violent, structive of cities. They may be upward, downward, or sidewise. They ay affect small areas or they may involve a large portion of a continent ocean basin. Without diastrophism there would be no continents.

idence for Diastrophic Movements

For purpose of discussion, the evidence for diastrophic movements may considered under two headings. The first will include the type of evi- nce which is not difficult to discern; the second will deal with evidence quiring prolonged examination of the structure of rocks, the study of ich often calls for considerable preparation and training.

Earthquakes and recent changes of sea level are within the power of servation of everyone. Though supposed by most people to be rare, rthquakes are very common. An earthquake is always front-page news, r it is destructive to the life and the works of man. In the great earth- ake of 1923 in Japan, 142,000 people were killed and an equal number jured. Aside from the major earthquakes that are reported in the news- pers, several hundred minor shocks are recorded yearly through seis- ographs. These periodic tremors are evidence that the "solid" earth not stable but is continuously undergoing crustal adjustments. When e records are examined to reveal the location of the disturbances, it is

FIGURE 114. EARTHQUAKE AREAS OF THE NEW WORLD
The earthquake areas are enclosed in heavy black lines

found that they occur mainly in two belts running round the earth sho in Figures 114 and 115. One belt is along the border of the Paci Ocean basin, and the other runs through the Mediterranean Sea and A and connects with the Pacific zone. The two earthquake zones coinc with the most recent mountains of the earth, and a large number of turbances in the Pacific belt are in islands near regions where the oc floor drops to abyssal depths. For example, the Pacific Ocean off Ja drops into the Tuscarora Deep, which has a maximum depth of twen eight thousand feet — one of the deepest sea beds known. Periodic tr ors, which will be further discussed at the end of the chapter, indic that the crust of the earth is under stress.

Evidence of recent changes of sea level is not very difficult to fi There are many old beaches, wave-built terraces, and wave-cut cliffs, fo inland far above the present level of the water. In the northeast par the Great Lakes District there are many places where the obvious sh

FIGURE 115. EARTHQUAKE AREAS OF THE OLD WORLD
The earthquake areas are enclosed in heavy black lines

es are several hundred feet above the present water level. This indi-
tes that the Great Lakes in recent geological history began to tilt in a
ıthwesterly direction. The tilting is assumed to have begun at the end
the last glaciation. Accurate measurements in the Chicago Area indi-
te a sinking of about nine inches for the past one hundred years. Other
idence of subsidence of land is furnished by valleys encroached upon
the sea, such as that of Hudson River, which was briefly considered in
e last chapter. But the most conclusive evidence for changes of level,
eding no expert interpreter, consists of shells of marine animals or ripple
ırks on hills found far inland. For example, Figure 116 presents a photo-
ıph taken several miles from Baraboo, Wisconsin. The natives called
s rock formation "washboard factory," since the sedimentary rock has
e appearance of corrugated washboards. The corrugations, now stand-
; vertically, are unmistakable ripple marks; shells of marine animals are
ınd embedded in the rock. It is obvious that this region was once the

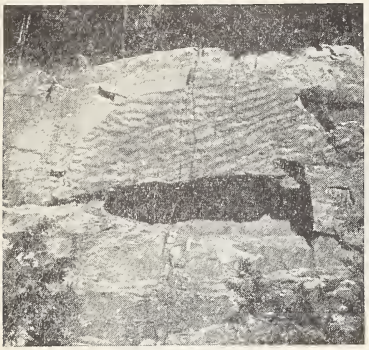


FIGURE 116
EVIDENCE OF DIASTROPHISM
"Washboard Factory," near Baraboo, Wisconsin. The ripple marks were made on a flat surface. The rock strata were elevated and then tilted to the present angle of about 90 degrees.

FIGURE 117
EVIDENCE OF DIASTROPHISM
Tilted Limestone Strata, Vermillion River, Deer Park, Illinois

bottom of a shallow sea or a flood plain which was slowly elevated. Aft elevation, this stratum was tilted by a later disturbance to an angle about 90°.

Folds

The structure of rocks, particularly those of sedimentary origin, in son places at the surface reveals evidence of past crustal movements. Sed mentary beds which were originally laid with parallel strata are fou buckled into folds. Where the beds are arched up, as in an upfold, th are called *anticlines*. Corresponding to these crests are downfolds in t form of troughs called *synclines*. In some places the arches and troug of the rocks extend only a few feet and are therefore easily discernible, b in most regions the folds are of very large dimensions and so complex th only a geologist can decipher the structure. The bending of brittle roc may at first sight appear as abnormal behavior. It should be realize however, that the bending did not take place in a few hours, but slow over long periods of time at depths where the pressure of the overlyi strata prevented the folds from breaking.

The small folds shown in Figures 119 and 120 are not typical or ve common. Erosion and subsequent movement make the study of t structure of a particular region especially difficult. Although a syncl usually forms a valley and an anticline a ridge, erosion reduces both i nearly a plain. It is clear, however, that investigation below the surf

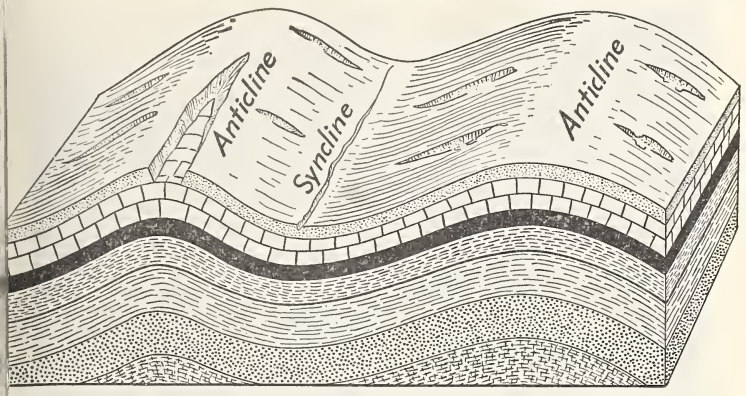


FIGURE 118. DIAGRAM OF A SYNCLINE AND ANTICLINE

ill reveal both upfolded and downfolded structures. Erosion may even verse the original structure and produce a valley by cutting into anti- inal beds. The methods used in the study of rock structures are beyond ne scope of this text.

Although the dimension of folds may vary from a few feet to a few miles, here are huge folds in the continents which extend for hundreds of miles. The great continental downfolds, or *geosynclines*, as they are called, serve s the basins of deposition of the eroded material and later may become the

FIGURE 119. SEDIMENTARY BEDS FORMING AN ANTICLINE
An anticlinical fold in sandstone and shales near Hancock, Maryland
(*Courtesy of U.S. Geological Survey*)

FIGURE 120. SEDIMENTARY BEDS FORMING A SYNCLINE
A synclinical fold near Hancock, Maryland. (*Courtesy of U.S. Geological Survey*)

seat of crustal movements. In contrast to geosynclines there are gre uplifted folds of large dimensions, called *geanticlines*. A study of gre mountain chains extending for hundreds of miles shows folded sedimenta strata of sandstones, conglomerates, shales, and limestones, indicati that these have been laid down in great troughs of deposition. As t sediments are eroded from the high portions of the continent, the tra ported material is deposited in shallow sea basins covering the geosy clines. When the material accumulates several thousand feet in thickne the basin sinks with slow downwarping and becomes a point of weakne During crustal movements of the strata the geosyncline may be fold into mountains. This topic is discussed in greater detail at the end this chapter.

Faults

Besides folding, there is another type of rock structure that indica crustal movements. The surface of rocks is not continuous but is int rupted in many directions by fractures or by breaks called *joints*. Wh the rock on one side of the fracture moves with respect to the other, t fracture is known as a *fault*. The fracture may be very thin, so that la it may close; or it may widen and rock débris may fall into it, thus obsc ing the relation of the two rock masses. The surface of the fracture alo which the movement has taken place is called the *fault plane*; this may vertical, horizontal, or inclined in any intermediate position. In an clined fault, the side that overhangs is the *hanging wall* and the side

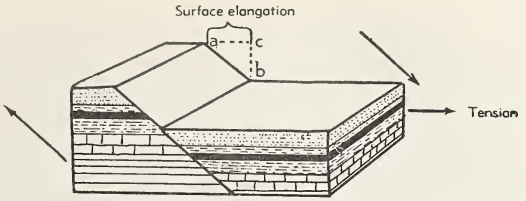


FIGURE 121. DIAGRAM OF A NORMAL, OR TENSION FAULT

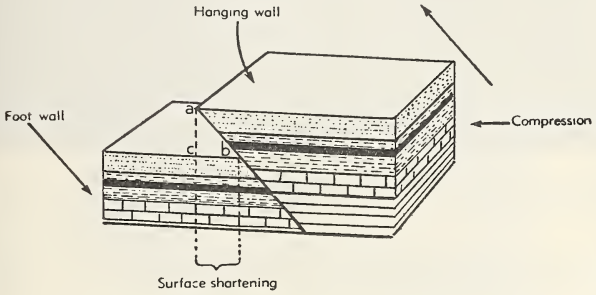


FIGURE 122. DIAGRAM OF A THRUST FAULT

eath is the *foot wall*. Faults are classified according to the relative dis-lacement of the two sides. In the *normal fault* (Figure 121), the hanging all has gone down with relation to the foot wall, and an elongation of urface results. This is shown in the diagram by line *ac*. Faults of this ype result from tension. If in a fault the hanging wall appears to have one up over the foot wall, it is called a *thrust* (or *reverse*) *fault*. As is shown n Figure 122, a thrust fault results from compression, and the movement roduces shortening of the surface, indicated by the line *bc*. When a fault levates one side of a rock with relation to the other so that a cliff is formed, is called a *fault scarp*. Many of our mountain systems have been built p through complex folding and faulting.

Unconformities

Let us suppose that in a shallow sea where there was an abundance of me-secreting organisms, limestone was deposited. The region slowly ose as streams brought in eroded débris, and the sediment became mostly ud, which ultimately changed to shale. The sea became more shallow, ne sediment changed to sand, and sandstones were formed. Then through rosion practically all the sandstone was removed; the beds now show arallel strata with a gradual change from one type of sedimentary rock

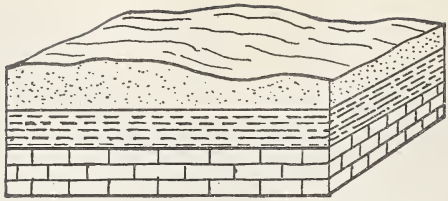


FIGURE 123. DIAGRAM OF CONFORMABLE STRATA OF LIMESTONE, SHALE, AND SANDSTONE

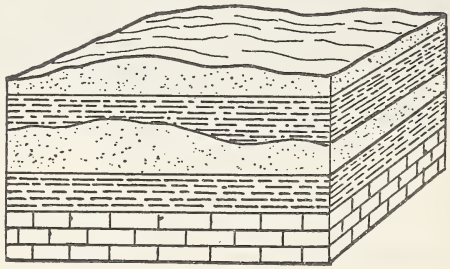


FIGURE 124. DIAGRAM OF EROSIONAL UNCONFORMITY

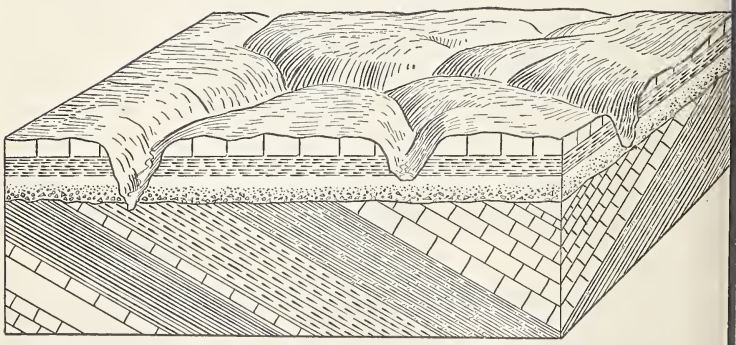


FIGURE 125. DIAGRAM OF ANGULAR UNCONFORMITY IN A SERIES OF SEDIMENTARY ROCKS

The lower beds were deposited horizontally, then uplifted, tilted, and eroded. During later submergence the upper series were deposited on the tilted beds, then lifted to the present position.

FIGURE 126. UNCONFORMITY IN ROCK STRATA

Conglomerate lying unconformably on edges of upturned agglomerate, northeast of Socorro, New Mexico. (*Courtesy of U.S. Geological Survey*)

o another. The strata in such series are said to be *conformable* with each ther.

In this hypothetical example, however, after most of the sandstone was roded away, if the region was again submerged and other sedimentary eds were deposited, the latter series of rocks would be *unconformable* with he first. The plane of contact between the two series of beds would be a *plane of unconformity.* Such a "break" in the strata, recording an ancient eriod of erosion, is important in geological history. If there is no folding elow the "break," that is, if the beds above and below the plane of unonformity have the same inclination, it is called a *disconformity.* If the eds in the lower series were folded or tilted before the other series were leposited, it is called an *angular unconformity.*

Unconformities are important records in attempting to reconstruct the robable past history of a particular region. For example, the angular nconformity represented in the diagram of Figure 125 indicates large rustal disturbances and a long period of erosion. The lower beds of imestones, sandstones, and shales form an angle with the younger upper orizontal beds. This indicates that the lower beds were first deposited s a horizontal series. Then they were uplifted and tilted. The mountains which were formed from these tilted beds were afterwards exposed o a long period of erosion until the folds were worn down to a low relief, hen submerged, and new sedimentary beds were deposited. After this edimentation the region was lifted above the sea level and erosion has set n anew, carving the present valleys.

Effects of Crustal Movements on Rocks

As we have seen, during crustal movements the rocks, particularly those which are deeply buried, undergo extensive metamorphosis under the influence of the great pressures and of the temperatures developed through friction and from radioactive changes. Rearrangement of crystals occurs, and new minerals may be produced by chemical reactions. In general, there are changes in hardness, crystalline structure, and cleavage. The general trend underlying all these changes is to produce a rock that is the most stable under the environment. Consequently, the rearrangement of minerals will be toward denser materials, enabling them to occupy less volume; crystals are rotated so that their long axis is in the direction of the least pressure. In this manner, a parallel arrangement of crystals results in some fine shales which may be changed to slates and mica schists. They tend to split into flakes or thin slabs parallel to the arrangement of crystals. Coarse arrangement of the crystals produces schists and gneisses.

Earthquakes

The relation of earthquakes to diastrophism was given in the beginning of this chapter. It was stated that earthquakes are one of the effects of diastrophic movements. The term earthquake is applied to all movements that produce shaking or trembling of the ground. The terror and destruction that earthquakes have brought to man have induced a careful study of the regions most affected by earth tremors and of the methods of detecting them. *Seismology* is the scientific study of earthquakes. It has accomplished far more in a short time than all the previous attempts to explain the tremors and rumblings as the wrath of the gods.

As previously mentioned, most earthquakes occur along definite belts in which there has been recent mountain building or where the work of gradation makes adjustments necessary. The sudden slipping of portions of the earth's crust in extensive faulting furnishes the impulse. Hard rocks are to a certain extent compressible and elastic, and the force of the movement of the fault is transmitted as vibrations or waves into the surrounding parts of the earth. Earthquakes are also frequent in areas where there are volcanic eruptions. The collapse of the roof of a cave or an extensive landslide may produce minor tremors.

Earthquakes are exceedingly common. Some thirty thousand occur each year. Most of the shocks are very slight. Earthquakes that cause considerable loss of life and property occur not more than once or twice a year. The loss of life is often due to sudden high sea waves caused by the sudden movement of the earth. In the earthquake which destroyed Lisbon on November 1, 1755, sixty thousand people were killed. The greatest part of this destruction was due to waves, sixty feet high, that

A = socket permitting free horizontal movement of pendulum W

M = upright mounted on base B on solid bed rock

D = recording drum driven by clockwork

W = pendulum weight supported only by the wire R and the socket joint A

F = pivot for stylus S

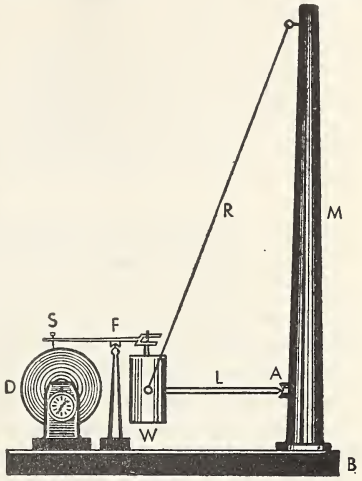


FIGURE 127. DIAGRAMMATIC SKETCH OF A SEISMOGRAPH (HORIZONTAL-PENDULUM TYPE)

ushed in one hour after the earthquake. Huge waves accompanied the arthquake of 1923 in Japan. The disastrous effect of earthquakes is due hiefly to the suddenness of the vibrations, rather than to the amplitude f the vibrations. A sudden shock with an amplitude of one-eighth of an nch will shatter a chimney. At the *epicenter*, which is the location on the urface above the subterranean place of origin of the disturbance, bodies re projected upwards.

tudy of Earthquakes

When a quake occurs, elastic waves in the surrounding rocks radiate in ll directions. When they strike the surface of the earth, they set up dditional vibrations which, locally, are often quite destructive. The lastic waves are sorted out according to their speed, as determined by an nstrument called a *seismograph*. This is essentially a pendulum with a ong period. A heavy mass of metal is suspended like a horizontal pendu- um. The base of the instrument is mounted on solid rock. The sus- ended mass of the pendulum remains essentially stationary when the round oscillates. The vibrations are magnified by means of a lever, and re recorded on the paper strip of a revolving drum, which is driven by lockwork. Such a record is known as a *seismogram*. In general, three ets of waves are recorded by the instrument, for as the waves travel out rom the center of disturbance they become separated into three more or

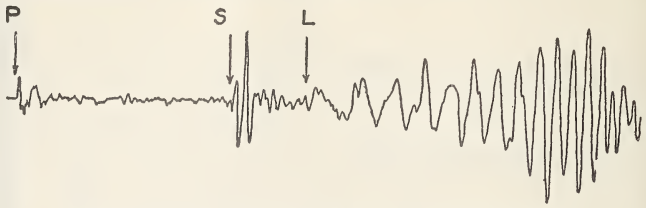


FIGURE 128. A SEISMOGRAM OF AN EARTHQUAKE
Arrows point to the beginning of primary (P), secondary (S), and long (L) waves

less distinct sets. Each set proceeds at varying speed, depending upo the density and elasticity of the rocks, as follows:

(1) *Primary Waves*: These are longitudinal (compressional) waves, an travel about six miles a second. They arise from compressions of the roc at the center of disturbance, and are similar to sound waves. They trav through solids or liquids.

(2) *Secondary Waves*: These are transverse waves, and travel about fou miles a second; hence they tend to lag behind the primary waves. Th secondary waves do not travel through liquids. Both the primary an the secondary waves travel along arcs beneath the surface of the eart and are called *body waves*.

(3) *Long Waves*: These waves travel slowest of all — about two miles second — and move along the surface of the earth. They are large transverse, and are set up when the body waves strike the surface of t earth.

There is a time lag between the successive waves, which varies with t distance between the earthquake center and the seismograph observato By means of curves called *time-distance graphs* it is possible to tell how f away the earthquake originated. Three observatories acting together a able to locate the center very accurately. As the earthquake waves a recorded at various stations, the distance to the center of the disturban can be calculated. The distance from each station is laid out as a radiu and a circle is drawn. The three circles thus drawn intersect at the poi of disturbance. When earthquakes occur in remote areas, the obser tories are often able to publish the location before word arrives from t stricken area.

The propagation of earthquake waves through the earth affords c siderable information as to the composition of the earth's interior. T topic will be treated in the following chapter.

Mountains

Examination of a world topographic map, which indicates differen in elevation between the various parts of the land, shows that mounta

are not scattered haphazardly over the continents. Most of the great mountains occur in groups which run parallel to the border of the ocean and continents. There are, it is true, some mountains which seem to be scattered over the land and do not occur in great chains; these have been either carved out of the land by stream erosion or are the products of volcanic activity. The great mountain chains which form the backbone of the American continents, and of Europe, Africa, and Asia, are the results of gigantic crustal movements.

Mountains Caused by Erosion. Mountains may be produced by differential erosion of rocks. The rate of erosion depends on the hardness of the rocks and, as was shown previously, deep canyons and high waterfalls have been eroded by streams. As a high plateau is dissected by running water, the more resistant parts remain as high ridges between stream divides. These ultimately may be carved to such heights as to be called mountains. The Catskill Mountains in New York are assumed to have been formed in such a manner. The strata of rocks is not folded or crumpled like those of the Appalachians but in many places are nearly horizontal. Such mountains of erosion are being slowly carved at the present time in many parts of western United States.

Mountains Caused by Volcanic Action. The volcanic type of mountains may occur singly, or in groups in the form of high cones and high plateaus. They are built by the piling up of lava, cinders, and the other products of volcanic activity discussed in the next chapter. The Hawaiian Islands, which rise high above the sea level, are great volcanic piles more than thirty thousand feet in height, built from the sea floor by volcanoes in that region. Other volcanic mountains appear as cones, either singly or in rows, in regions which are relatively flat and do not show crumpled and deformed rock strata. The absence of these features and the presence of wholly igneous rocks and other structural details indicate that these elevations were formed by volcanic activity.

Mountains Caused by Crustal Movement. Most of the great chains of lofty mountains are the result of huge crustal movements. Examination of the structure of these elevated rock masses reveals large numbers of conglomerates, sandstones, shales, and limestones, all of sedimentary origin. Though the original sedimentary rocks have been deformed, the stratification and the presence of marine shells and fossils clearly indicate that these arches were once the flat bottom of shallow seas in areas of deposition. The folded strata of these mountains also indicate that the sedimentary beds were pushed upward in the form of arches or folds by intense compressional forces acting horizontally from both sides. To visualize roughly the formation of folds, take a dozen different colored pieces of cardboard about eight inches square, arrange them flat on top of each other, and hold with the edges resting against the palms of the hands. Push the palms toward each other, so that the layers of the card-

board crumple and arch upward. It will be noted that as the fold of the cardboard "strata" arches upward, there is a shortening of the original flat distance from edge to edge. To state the same thing in another way, if after folding the cardboard strata, the folds are leveled by pulling the palms outward, there will be an increase in the width of the cardboard "region." In the same manner, if the mountain folds of the Appalachians and the Rockies were leveled out again by pushing downward from above, these regions would become thirty to fifty miles wider; hence there was a shortening of the North American continent thirty to fifty miles when each mountain chain was made. The present mountain heights do not indicate the original height of the fold, because erosion has been actively at work since their formation. Many mountains, for example the Appalachians, represent only the stumps of the once high peaks which were peneplained and then uplifted again.

Besides the fold mountains just discussed, whose structure consists of large synclines and anticlines, there are mountains which are assumed to have been produced by *faulting* on a gigantic scale. Assume that the North American continent from the Atlantic to the Pacific is divided into hypothetical segments or blocks five hundred miles in length north and south and a hundred miles in width, east and west. These blocks of rock are mostly granitic and rest at lower depths on top of heavier or denser basaltic rock. By movement of these blocks it is possible to explain the formation of mountains due to faulting. For example, one block may slip down several thousand feet, leaving the adjacent block in its original position as a steep mountain on one side. Several adjacent blocks may move, one being elevated to mountain height, and the other depressed. In general, the movement is of the fault type and such mountains are called *block* or *fault mountains*. An example of this type is the Sierra Nevada range in California. This mountain is a block about four hundred miles in length and seventy-five miles in width. The approach from the Pacific side is a long, gentle slope, while from the eastern side the approach is precipitous and abrupt. This region is the seat of violent earthquakes, a phenomenon of active present-day faulting.

Origin of Mountain Systems. We cannot discuss here all the structures of mountains. Even the two types of mountains which are assumed to have been produced by crustal movements on a gigantic scale are the exceptions rather than the rule. The great mountain systems are very complex in their structure. They show evidence of complex folds, normal faults, thrust faults, igneous intrusions, stream dissection, and the effects of other forces. The Rockies, the Alps, and the Himalayas are complex in structure and any detailed treatment is beyond the scope of this text. For our present discussion it will suffice to note a few general features about them. Many of these mountain systems, like the Andes, the Japanese mountains, and the Philippines, are fronted by troughs of deep

ceanic depressions which may be regarded as open geosynclines or water-illed downwarps. As noted in the introduction to this section, there seems o be a general trend in mountain-building along continental margins. Many of the mountain belts like the American Cordilleras and the Appalachians are parallel with the continental margins and straight in plan, while others like the Alps and the Himalayas bend in the form of a bow. Some of the huge folds found in these complex mountains are composed of edimentary strata, five thousand to twenty thousand feet or more in hickness, thus indicating a tremendously long period of erosion or deposition preceding the mountain or orogenetic movement. The relation between the folded sedimentary strata of the mountain, and the geosyncline n which it was once horizontally deposited, is a fundamental one in rogenesis.

Based on this brief discussion, a sketchy outline of the origin of these omplex mountain systems may be given. Bordering a relatively high ontinent which is being eroded, there is an elongated shallow basin or eosyncline on which the eroded material is carried by the streams and eposited to form sedimentary beds. As the load of sediment accumulates n thickness, the geosyncline sinks and in this manner deposits several iles thick are formed. The transferring of material by erosion from one ection to another disturbs the equilibrium of the crust, and during periods f crustal movements the sedimentary beds being pushed from either side y compressional forces begin to be arched up in the form of a fold as

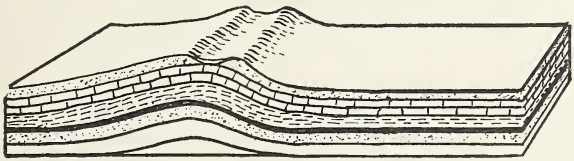


FIGURE 129. OROGENIC FOLDING
(*Compare with Figure 130*)

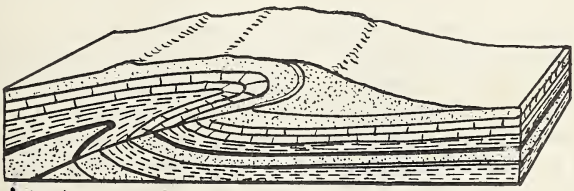


FIGURE 130. THE COMPRESSION FOLD PASSES INTO A THRUST FAULT
(*Compare with Figure 129*)

shown diagrammatically in Figure 129. With increase in the compressional forces, steep folds are formed until it may finally develop into a thrust fault as shown in Figure 130. As the soft sediments of the geosyncline are arched into steep folds, the crest breaks, and the fold passes into a thrust fault. The rock strata may be driven over the underlying mass for several miles. For example, in the Northern Rockies great amounts of rock strata were driven eastward for more than five miles over the rocks beneath. The rocks underneath which are overridden suffer extreme deformation. In the Alps the older rocks were pushed over the younger rocks for more than fifty miles. Although these older rocks have been mostly removed by erosion, some remain as isolated peaks standing over younger strata.

Causes of Crustal Movements

The various theories proposed to explain mountain-building and other crustal movements are of the speculative type and should properly be called speculative hypotheses. It is impossible to test any of these hypotheses. Observations are impossible since the inner layers of the earth are inaccessible. The crustal movements involve inner layers of the earth several hundred miles deep, and forces of magnitudes that are staggering to the imagination. Nevertheless, the geologist, the geophysicist, and the geochemist attempt, by piecing together all the available evidence from all fields of science, to formulate plausible hypotheses which will explain in a natural way the elevation of huge masses of rocks to dizzy heights.

The early speculations on mountain-building began with the formation of the earth. It is assumed that the young earth was liquid for at least a part of its history. During this period some of the heavier minerals and elements sank toward the center, while the lighter layers began to cool and to form the crust. The formation of the crust reduced the rate of cooling tremendously, but did not entirely arrest it. Accordingly, there was, and still is, a constant loss of heat by thermal conduction through the crust. Ultimately the outer shell had to readjust itself to the shrinkage of the inner shell and was horizontally compressed, thus initiating all the complex crustal movements.

The original contraction hypothesis has been modified to fit an earth which has essentially a solid core. Measurements from borings and deep mines indicate that the earth is increasingly hotter inward from the crust. Some of the heat is caused by rock movements due to the tremendous pressure exerted by the overlying rock layers. This pressure has been estimated at about 3.5 million atmospheres at the center of the earth, or roughly fifty million pounds per square inch. There is also some heat produced by radioactive changes (cf. page 458). The temperature near the center has been calculated at about 2000° C. Hence the various elements

nd minerals in the great depth are under conditions vastly different from hose at the surface. Under these enormous pressures and temperatures he various minerals are rearranged into denser compounds which settle ward the interior. Since the inner core contracts, the outermost solid ayer follows, and is horizontally compressed. This necessitates profound novements in the crust, which we see as faults, thrusts, folding, mountain-uilding, and other adjustments.

Arguments against the contraction hypothesis are the calculations of eochemists which indicate that the disintegration of radioactive materials ithin the crust furnish far more heat than is lost by thermal conduction t the surface. It is assumed, therefore, that more heat is generated inside he earth than escapes. Some geochemists have even proposed that the xcess heat ultimately accumulates and gives rise to subcrustal currents hich cause mountain-building and volcanic activity. Accordingly, a part f the accumulated heat is transformed into kinetic energy to produce nountains while the other escapes through the rise of hot lavas.

Another school of geologists attempts to escape the contraction hypothe-s by assuming that the primary cause is the increasing density and settling f the heavy minerals toward the center, which produces subcrustal urrents and in turn causes downsliding of large segments of the lithosphere. here is evidence from measurements of gravity that the dominant ma-erial of the upper sublayer in the continental lithosphere is granitic. his layer of granite lies on a substratum of heavier basaltic rock. Accord-ng to this view the oceanic segments, which are heavy, have sunk and have ushed the lighter granitic segments of the continents upward. Over a ng period of time there should be a condition of crustal equilibrium or *sostacy* between the various segments. As material is eroded from the ntinental segments and dumped into the oceanic basins, the crustal quilibrium is disturbed. This, together with the settling of the heavier inerals toward the center of the earth, is assumed to cause downsliding f the oceanic segment. This in turn causes the substratum rock to flow nder the continental segments, forcing them to rise. The downsliding an act as a wedge against the geosyncline and fold the sediments, giving se to thrust faulting.

Another hypothesis proposes the drifting of continental blocks as a esult of subcrustal currents. According to this view, the mountain hains of the globe were formed by the horizontal crushing of geosynclines hich lay in front of slowly migrating continents. In the formation of lps, Africa is assumed to have moved northward, crushing the old editerranean geosyncline. Similarly, the Rockies were formed when he North American continent slipped away from Europe to the west. he westward migration of the American continental block involved such rce that the strata of the Rocky Mountain geosyncline were thrust into nountain folds and thrusts. The problem appears to be a complicated

one, and these hypotheses must remain as speculations which will stimu late further research.

In concluding this brief discussion on the causes of diastrophism, th student is reminded that all the explanations are at best speculativ hypotheses. The most we can say is that the forces involved in th crustal movements that gave rise to the great mountain chains were tre mendous and that we do not know the ultimate causes, but on the basi of the available evidence we have a number of speculative hypotheses which may serve in the quest for an explanation. As new evidence i obtained, our hypotheses will be corroborated, changed, or discarded.

SUMMARY

1. By building up land, diastrophism is one of the forces which tends to offs the work of gradation.
2. Earthquakes and recent elevation and subsidence of land give evidence o diastrophic movements.
3. The study of rock structure reveals evidence of crustal movements in th past. Folds and faults indicate ancient diastrophic movements.
4. Synclines are downfolded rock structures, and anticlines are upfolded crest Geosynclines and geanticlines are continental folds of very large dimension
5. Faults are movements of one rock mass with respect to another along a fra ture. Tensional forces produce a normal fault, and compressional forc produce a thrust fault.
6. Most mountain systems have been built by complex folding and faulting rock strata which have been deposited in ancient geosynclines.
7. The ultimate causes of crustal movements are not known, and the hypothes which attempt to explain them are speculative in character.
8. An unconformity between two rock masses indicates that there was a peri during which the lower mass was eroded followed by a period of submergen during which sedimentary strata were laid over the eroded surface.
9. Earthquakes are movements which produce trembling of the ground, an occur along definite belts of recent mountain-building.
10. Through the seismograph earthquake waves are differentiated into thr types, each traveling at a different speed. The long waves which travel tw miles per second and move along the surface of the earth are destructiv of buildings.

STUDY EXERCISES

1. Enumerate all the available evidence that indicates movements of the earth crust. Arrange the evidence in two sections: the first to include eviden which is easily discerned; and the second, evidence which requires conside able training.
2. Make rough drawings of a syncline, an anticline, a normal fault, a thru fault, and an erosional unconformity.

3. Study Figures 114 and 115 in the text. Locate the regions of crustal instability and name them: in (*a*) North and South America; (*b*) the Mediterranean and the Near East; (*c*) Asia; (*d*) the Pacific region.

4. Make a table of earthquake waves according to the following form. Explain how seismographs are used to locate the epicentrum.

Type of Wave	Speed in miles/sec.	Type of wave motion	Probable origin
Primary.....			
Secondary.....			
Tertiary.....			

5. In a canyon the following strata are encountered. Reconstruct the probable history of the region.

Soil
mantle containing pebbles
clay
sandstone
shale
coal
shale
limestone
shale
coal
shale

6. Briefly discuss: (*a*) formation of mountains by folding and faulting; (*b*) formation of mountains by erosion and by volcanic forces; (*c*) theories proposed to explain mountain-building and causes of crustal movements.

FOR FURTHER READING

1. Croneis, C., and W. C. Krumbein, *Down to Earth.*
Chapter 16 gives a general discussion of the surface evidence for diastrophic movements. Chapter 17 gives a discussion of folding and faulting and Chapter 18 of earthquakes.

2. Longwell, C. R., A. Knopf, and R. F. Flint, *Outlines of Physical Geology.*
Chapter 11 gives a thorough discussion of diastrophism and its effects. Metamorphic rocks produced by crustal movements are discussed in Chapter 13 and earthquakes in Chapter 12. The structure and history of mountains and the ultimate causes of crustal movements are discussed in great detail in Chapter 14.

3. Agar, W. M., R. F. Flint, and C. R. Longwell, *Geology from Original Sources.*
A very interesting account of the subsidence and elevation of the temple of Jupiter Serapis in Pozzuoli Italy within historic times will be found in Chapter 10. In the same chapter appear graphic accounts of the San Francisco and Charleston earthquakes.

10

Mountains of Fire

TO MOST OF THE ANCIENTS, the eruption of a volcano was terrifying. They heard the earth rumble, and from time to time felt ground-shaking tremors. They saw brilliant flashes alternating with midnight darkness, followed by a series of explosions sending out clouds of smoke from the vent of the mountain. The Romans called such a fiery mountain the home of Vulcan, maker of war implements among the gods. Today the term *volcano* designates an opening or fissure from which gases, molten rock, and solid rock fragments are ejected. The term is usually associated with a steep cone having an opening at the top called *crater*, but a number of volcanoes are known without the cone structure. The characteristic feature of a volcano is an opening through which hot materials are emitted from the interior parts of the earth.

More generally, the term *volcanism* includes all movements of molten rock and the phenomena that are associated with these movements; it is a force which, together with diastrophism, tends to offset the work of gradation by building up land. Studies of the igneous rocks of the crust, both at the surface and at some depth, indicate that molten rock called *magma* rises along fissures from depths of thirty to forty miles toward the surface. There are two phases in the movements of magma. In one, it fails to reach the surface and solidifies underground, forming igneous rocks which when later exposed by erosion are called *intrusions*. In the other phase the mobile magma rises along fissures, flows over the surface, and solidifies, forming igneous rocks called *extrusions*.

By far the greater part of the rocks found in the outer part of lithosphere are of volcanic origin and therefore are called *igneous*. This fact and the present wide distribution of active and extinct volcanoes indicate that volcanism has been the most important constructive force building up the structural elements of the earth.

Eruptions

The nature of volcanic activity, or *eruptions*, depends on the nature of the ejected materials. The eruption of a volcano may lead to a quiet

ow of molten rock called *lava*, or may be explosive, giving off large quantities of gases with little or no flow of liquid rock; still other eruptions clude the ejection of both gases and solid rock material. The fluidity the magma and the amount of gases in it determine the type of eruption. The lava coming up to the surface may flow through fissures and cover rge areas without building the characteristic mound of volcanoes. In e fissure type of eruption, it may flow through one or more huge cracks. Iceland, one fissure is nineteen miles long and in many places four hunred to six hundred feet deep. In the North American continent, huge saltic flows covered parts of Idaho, Washington, and Oregon — a total about two hundred thousand square miles. The area covered by these saltic flows, often called the Columbia River basalts, has an average ickness of about five hundred feet and in some places four thousand feet. milar basaltic flows of great thickness covering large areas are found in azil, Argentina, and India. The outpouring of lava through fissures oceeds quietly. As the flow continues the lava slowly solidifies on the les of the fissure, and in time the passage to the surface closes.

The eruption of some volcanoes is often preceded and accompanied by rthquakes and rumblings of the ground; these rumblings and the explosive eruptions are due to the gases held under pressure in the rising agma. In the eruption on the island of Tamboro Sumbawa in the Dutch ast Indies in 1815, the rumblings were heard over an area of about a ousand miles. In the explosion, the surface of the vent is blown up as ast and ashes, leaving a pit which marks the site of the wrecked cone. In e explosion of Tamboro, which is the greatest recorded in history, about irty-five cubic miles of material were blown into the air and fell on an ea of a million square miles. The pit formed by this explosion is nearly miles in diameter. In other volcanic eruptions the outpouring of lava oceeds after initial explosions which release the gases under pressure, companied by smaller periodic explosions which send fragmental materials upwards. The solid fragments vary in size from fine dust to large cks; part of these are derived from the solid walls of the volcanic channel, hers from the liquid rock which is thrown upward by the escaping gases d solidifies in its flight through the air. Between the two types of eruptions — the quiet type, which emits fluid lava, and the violent explosive pe, which ejects mostly ashes and great amounts of gases — there are termediate phases of volcanic activity.

The volcanoes of Hawaii illustrate the first type of activity. The island s been built by basaltic flows from the bottom of the ocean. Mauna a rises 13,700 and Kilauea 4000 feet above sea level. The crater of ilauea, called Halemaumau (Everlasting House of Fire), was 1300 feet diameter prior to 1924. It contains a lake of basaltic lava, until rently kept boiling by the escaping hot gases. The temperature of the va ranges from 1000° to 1200° C. The lava column is believed to rest on

a solid bottom through small cracks and wells in which the lava rises the surface of the crater. In 1924 the column of lava dropped about seve hundred feet in the pit, and this fall was followed by explosions which se vast clouds of gases and rock débris more than eight thousand feet in the sky. The pit was enlarged to three thousand feet across. No heav explosions had occurred for one hundred and thirty-four years up to 192 and it is thought that sudden penetration of water into the hot roc generated the superheated steam which caused the explosions.

Violent explosive activity is illustrated by the eruption of Tambo mentioned above and the explosion of Mont Pelee on Martinique, a island of the West Indies. The most catastrophic eruption of Mont Pel occurred on May 8, 1902, when after a week of little activity it blew out great cloud of superheated steam, laden with hot dust, which rolled dow from the mountain toward the sea, killing the twenty-eight thousand i habitants of the city of Saint Pierre, which was situated six miles from t volcano. No lava was ejected in this eruption.

The intermediate phases of volcanic activity are illustrated by the vo canoes of the Mediterranean region. On Lipari Island near Sicily, t lava of the volcano is viscous, and crusts solidify on the vent until g pressure accumulates and erupts mostly fragmental material. Not f away the volcano of the island of Stromboli erupts with successive mi explosions. Active from antiquity, its visibility at night has given it t name of "the lighthouse of the Mediterranean." Its eruptions consist the upward ejection of molten lava, which falls mainly back into the crat and the expulsion of clouds of glowing gases. Vesuvius, the best know volcano in history, is situated above Naples. Prior to A.D. 79, there h been no record of any eruption, although the Romans had recognized t site as a volcanic region. In A.D. 79 a violent eruption blew off the upp part of the cone, sending out vast quantities of cinders and ashes whi buried the cities of Herculaneum, Pompeii, and Stabiae. There was lava flow. The eruption is graphically described by Pliny the Young in a letter to Tacitus. Minor eruptions occurred between A.D. 79 a 1538; in the latter year a hill of four hundred and forty feet arose acr the bay during a week's activity. Eighteen thousand persons were kill in an eruption in 1631. The last great eruption was in 1906, during whi lava and tremendous amounts of gases and ash were emitted. Since th time its only activity has consisted in sending up clouds of steam.

In the United States there are many sites of recently active volcano The flow of lava from a volcano near Grants, New Mexico, is still to seen, in the form of black frozen rivers along the road leading to Alb querque. Mount Lassen in northern California had a small eruption 1914. Its present activity is confined to mud geysers. This illustra the life cycle of a volcano. At first there is considerable activity; a co is built and intermittently changed. Finally the volcanic activity

FIGURE 131. KILAUEA LAVA LAKE, CALDERA OF HALEMAUMAU, HAWAII

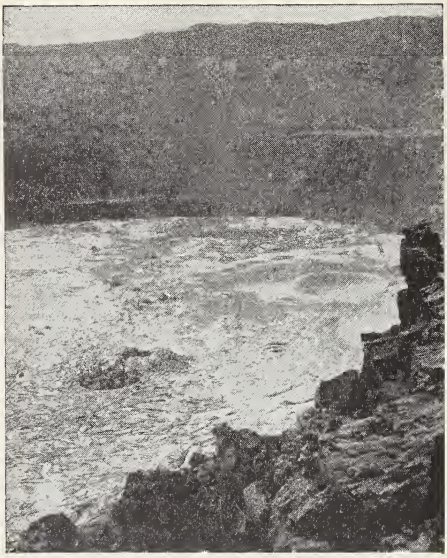


FIGURE 132. WEST WALL OF HALEMAUMAU, HAWAII, AND PART OF CRATER FLOOR
(*Courtesy of U.S. Geological Survey*)

minishes, the vent closes, and the solidified material below slowly coo
During this last phase, water percolating below becomes heated and giv
rise to hot springs, geysers, and *fumaroles* (vents from which gases escap

By successive eruptions volcanoes build structures which usually have
conical shape. If the ejected material consists mostly of cinders, the co
is steep; if a considerable amount of lava is emitted, as from the volcano
of Hawaii, a plateau structure with gentle slopes is built up. A successi
of lava flows and cinders produces composite cones with symmetrical wal
Mayon volcano in the Philippine Islands is considered one of the be
examples of a composite cone.

Products of Volcanic Eruptions

The chief products of volcanic activity are gases, fragmental materi
and lava. The composition of gases varies with various volcanoes a
probably with various stages of eruption. The greater part is stea
Sulfur gases are abundant in the Mediterranean volcanoes, while those
Alaska contain hydrochloric and hydrofluoric acids; ammonia, carb
dioxide, carbon monoxide, and other gases have been found to be emitt

FIGURE 133. SCORIA
Grants, New Mexico

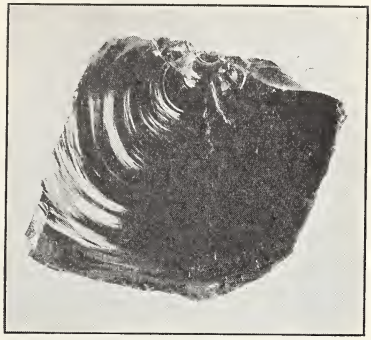


FIGURE 134. OBSIDIAN
Lake County, Oregon

)m volcanic vents. It will be noted that a number of these gases are isonous.

Fragmental material thrown up from volcanoes originates either from e sides of the crater or from ejected lava. As the magma comes near e top, the pressure is released, and the expanding gas carries with it mps of viscous molten rock which solidifies rapidly as it sails upward rough the air. If the mass is large, it falls back either on the crater or on e sides of the cone; depending on its size, it is called a *bomb*, *ashes*, or *nders*. If the size of the particle is very small, the result is *volcanic dust*, nich is carried to great heights and to great distances. Deposits of lcanic dust of several hundred feet in thickness and covering many uare miles are known.

Lava has a variable composition. A preponderance of ferromagnesian inerals gives black *basaltic* lavas. An excess of silica gives light *felsite* vas which on cooling may result in either rhyolite or andesite rocks, pending on the amount of quartz present. Most volcanoes emit asaltic lavas. The fluidity depends on many factors, especially composi-)n and temperature. Lava within the crater has a temperature of from 00° to 1500° C. and as it issues from the crater it is still red-hot. As it)ws it begins to cool. The crystallization and texture depend on the te of cooling, the composition, and the amount of gases that it contains. Many solidified lavas have numerous pores formerly occupied by the gases. the pores are so abundant that the rock has a spongy structure it is alled volcanic *scoria*. The upper part of some lavas, particularly those hich contain large amounts of silica and are viscous, may form a froth-ke rock owing to the escaping gases. Such froth-like rock is called *umice*, and it will float in water for some time.

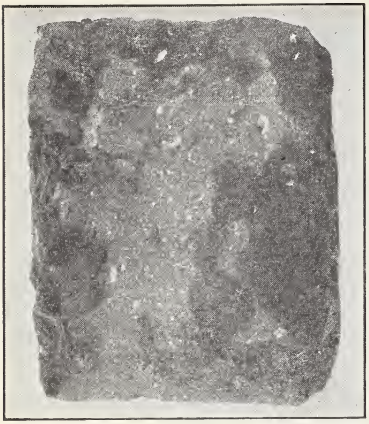


FIGURE 135
BASALT (AMYGDALOIDAL)
Salida, Colorado

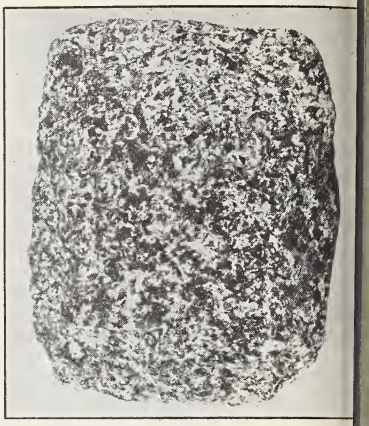


FIGURE 136
GABBRO-DIORITE
Salem, Massachusetts

Intrusions

When magma solidifies without reaching the surface of the earth it giv rise to igneous rocks which are named according to their shape and the relation to the surrounding rocks. These intrusions may later be expos at the surface of the earth as a result of removal of the overlying rocks b erosion. Intrusions of huge dimensions enlarging downwards to unknow depths are called *batholiths* (or, deep rocks). The cores of many mounta ranges are made up of immense batholiths, indicating that these gigant

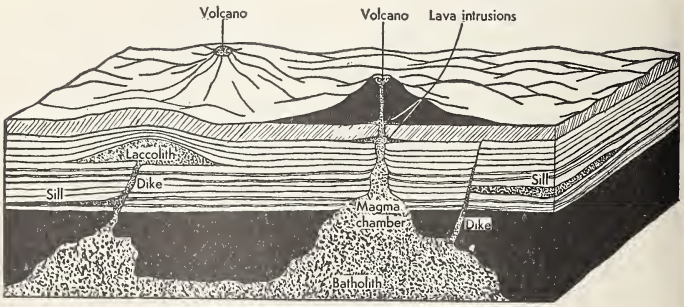


FIGURE 137. TYPES OF INTRUSIONS

Molten magma forcing its way into fissures forms dikes; where injected between beds rock it forms sills, or, by upheaving overlying strata, it forms laccoliths. Batholiths assumed to have been the feeding sources of all other intrusive bodies and also of volcan

rusions occurred during or after large crustal movements. A concep-
n of the dimensions of batholiths may be obtained from the exposed
face of the batholith in central Idaho which covers an area of sixteen
usand square miles. The
ks of most batholiths are
rse-grained granites.

Magma may work its way
ween cracks and fissures
pre-existing rocks, usually
imentary. If the crack is
tical, or nearly so, the
dified intrusion is called a
e; if the fissure is parallel
the layers of the sedi-
ntary rock, the solidified
rusion is called a *sill*. Lava
y produce an arch by
shing upwards the overly-
strata; then the intrusive
ss is called a *laccolith* (or cis-
n rock). Figure 137 shows
grammatically the various
es of intrusions.

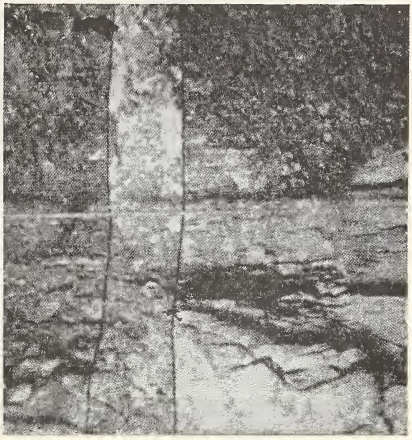


FIGURE 138. DIKE IN COAL MINE IN POPE COUNTY, ILLINOIS
(*Courtesy of Illinois State Geological Survey*)

FIGURE 139. SILLS NEAR TOWER FALLS, YELLOWSTONE PARK, SHOWING COLUMNAR JOINTING
Distant view shows relation to other rock formations
(*Courtesy of U.S. Geological Survey*)

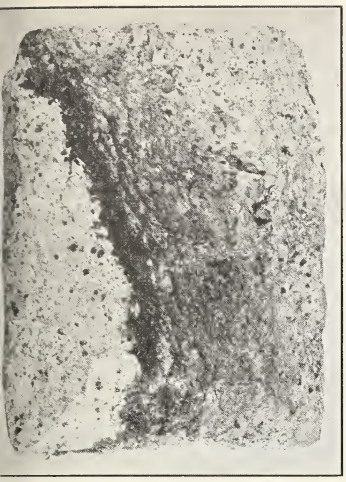
Dikes and sills are common. The best known sill in America is t
Palisade sill on the west side of the Hudson River in New York, and dik
are numerous in the Colorado Rockies. Both sills and dikes show bak
zones on the layers of rocks which they intrude, particularly in the regio
adjoining the intrusion. Many metallic compounds deposit on th
contact zones. Ninety per cent of the world's nickel comes from a sill
Sudbury, Ontario; gold and silver are mined from such intrusions in Coba
Ontario. Similarly, gold is found in many districts of Colorado in dik

As mentioned in the section dealing with the deposition effected
ground water (page 148), many mineral vein deposits are thought to ha
been formed by ground water coming in contact with igneous intrusio
The water dissolves the metallic compounds and deposits them alo
fissures, thus forming metalliferous veins.

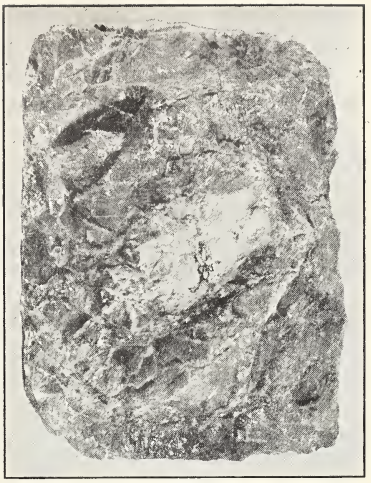
Intrusive and Extrusive Rocks

The mode of formation of igneous rocks was briefly discussed in Cha
ter 8. It was stated that the color and texture of a rock depends on
chemical composition and on the geologic environment in which the ro
was formed. Rocks formed as a result of a volcanic eruption di
markedly in appearance from the rocks formed by solidification of mag
at great depths. The chief differences are in the size, shape, and arran
ment of the individual crystals of the minerals which make up the ro
these characteristics, which are summed up by the term *texture*, are t
large extent determined by the rate of cooling of the liquid rock. I
evident that the solidification of lavas at or near the surface of the ea
will take place at a much faster rate than the solidification of magma
great depths, where it is insulated by the large amount of surround
rock.

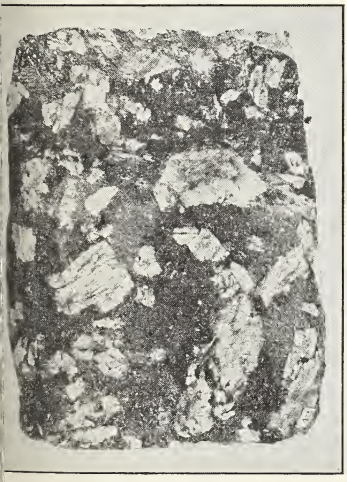
Granite and rhyolite rocks do not differ greatly in chemical compositi
Both contain about the same amounts of quartz, feldspars, and ferrom
nesians; although individual samples may differ widely, it is possible
find a specimen of granite and a specimen of rhyolite with little chem
difference. But physical examination of two such rock specimens
disclose some important differences. In the granite, even by a superfi
examination, it is possible to distinguish large individual crystals of bl
mica (biotite), but these are not apparent in the rhyolite specimen.
amination of a thin section of granite through a microscope shows that
black mica has well-defined crystal faces, and its feldspars have m
of the crystal faces developed, but its quartz crystals have only a
crystal faces well developed, and these seem to be crowded in between
crystals of black mica and feldspar. From these observations we can i
that, in the formation of granite, quartz was the last mineral to crystal
out, and that mica crystallized out first, followed by feldspar. Since
crystals in granite are large as compared with those in rhyolite, we can i



Rhyolite
(Deadwood, South Dakota)



Felsite
(Hyde Park, Massachusetts)



Diabase Porphyry
(Cape Ann, Massachusetts)

Syenite-Hornblende
(Cuttingsville, Vermont)

FIGURE 140. IGNEOUS ROCKS

that the cooling was very slow and that the individual crystals had suffici time to grow to large size. On the other hand, the cooling of lava t resulted in rhyolite rocks was relatively rapid; a large number of crys began to form simultaneously, and only few crystals had sufficient ti to grow; and hence most of the crystals grew to small size, forming a fi grained rock.

By the use of the reasoning illustrated in the preceding paragraph i possible to reconstruct the probable mode of formation of the various ty of igneous rocks. First, of course, we divide the rocks on the basis of t appearance into coarse-grained, fine-grained, and glassy; the latter do have discernible crystals, but appear as homogeneous solids similar to gl A number of rocks with large conspicuous crystals imbedded in a mas very small crystals, called *porphyries*, can be considered intermediate tween the coarse and the fine-grained.

A large mass of magma which moves toward the surface along fissu and cracks heats and ultimately melts part of the solid rocks with wh it comes in contact; these rocks may be sedimentary, metamorphic igneous in origin. Thus in its upward movement the chemical comp tion of the magma is changing, with new chemical reactions taking p and new minerals being formed. If the upward movement of the ma becomes slow as a result of loss of heat and consequent loss of fluidit point may be reached where crystallization begins long before the ma has found its way to the surface. The resulting intrusions may be ba liths, dikes, sills, or laccoliths. The type of intrusive rocks formed pends largely on the chemical composition of the magma, and to s extent on the pressure. If the amount of metallic oxides present in magma combine with silicon dioxide to form ferromagnesian minerals feldspars and there remains an excess of silicon dioxide, the rock will granite. As outlined in the preceding paragraph the ferromagnesian m erals, biotite or hornblende, separate out first, followed by the feldsp lastly the excess or uncombined silicon dioxide crystallizes out as qua filling the spaces which are left by the crystals of the other minerals. the chemical composition of the magma is such that there is no exces silicon dioxide but an abundance of feldspar and less ferromagnesian, resulting rock is *diorite*. And finally if the ferromagnesians predomi over the feldspars, the resulting rock is a coarse-grained dark rock ca *gabbro*.

When the magma rises to the surface and pours out from a volcano lava flow, the extrusive rocks are mainly either fine-grained or glassy. the composition of the magma is highly silicic, as is true of granites, the trusive rock is *rhyolite*; if the composition is intermediate, as in the cas diorite, the rock is *andesite*; and if the ferromagnesian minerals predo nate, the dark rock is called *basalt*. In a lava flow the conditions crystallization are not uniform. In the beginning, while the mass is v

)t and fluid, some individual crystals of minerals may develop to a size at can be detected by the eyes, until the cooling is very rapid and the nole mass crystallizes out into minute crystals. Therefore some rhyo- es may contain well-defined crystals of biotite, feldspar, and quartz t in mass of fine crystals, whereas another specimen may consist entirely such minute crystals that they cannot be distinguished by the unaided e. When this is so, it is very difficult to tell a rhyolite from an andesite, d such rocks are usually called *felsites*.

The crystallization of minerals may begin before the magma reaches e surface. A rock thus formed will show in its texture the changed nditions of crystallization. In an environment which permits slow cool- g, large crystals will be formed, in contrast to the minute crystals formed the surface. These are porphyritic rocks. A granite porphyry con- ts of well-defined crystals of biotite, feldspar, and quartz set in a mass very fine crystals similar to those found in rhyolites. When the rate cooling of a lava flow is very rapid and there is an absence of gases thin the liquid rock, solidification in a glasslike homogeneous mass re- lts. If the volcanic glass is brilliant, it is called *obsidian*; and if dull, *'chstone*. Finally, among the rocks formed by igneous activity are ssed those which are formed by compression and cementation of the gmental material ejected in volcanic eruptions. Rocks from coarse gmental materials are known as *volcanic breccia*, and those from finer terials are known as *tuff*.

lcanic Zones

From the foregoing discussion, we may conclude that volcanism has sted ever since the earth took shape, and that the rise of magma has curred many times in different parts of the earth. The present volcanoes, ich number about four hundred, are mostly of recent origin; a very large mber of volcanic cones are extinct. The distribution of the active vol- noes follows remarkably the earthquake zones and the zone of the most ent rugged mountains. Reference to the map in Figure 114 shows that e zone is along the Pacific Ocean basin, forming the famous "belt of fire," m the tip of South America to Alaska, from Alaska to Japan, from Japan the Philippines. The other zone (the Mediterranean) extends east d west, from Central America through the West Indies to the Azores, e Canary Islands, and the Mediterranean; from the Mediterranean rough Asia Minor and Persia to the East Indies, where it crosses the cific belt.

Some famous volcanoes have already been mentioned. Others are na in Sicily; Krakatoa on a small island near Java and Sumatra, which s practically blown up in 1883 in one of the greatest explosions within torical times; Fujiyama in Japan; and Katmai on the Alaskan Penin- a. The distribution of volcanoes and young mountains along the same

zone points to some relation between the two. The conclusion is draw that since mountains are produced by extensive folding and faulting (fra turing), the folded zones develop fissures clear through the solid crust the earth. Through these fissures the magma rises, causing the volcani eruption and producing intrusions. The question, however, remains to the source and upward movement of the magma. An answer must in volve an elementary discussion of the interior of the earth.

The Interior of the Earth

Thus far we have spoken repeatedly about the composition of the out part of the earth, but have avoided any discussion of the composition the interior. Of this we have no direct knowledge, because we have means of observing the nature and structure of the inner parts of t lithosphere. If we consider that the earth's radius is about four thousan miles and that man has penetrated scarcely more than two miles und the surface, we realize that we directly know less than one-thousandth one per cent of the volume of the lithosphere. The problem becom difficult when we consider that there is evidence indicating that the interi is different from the outer rocks. For example, the average density of t rocks that come under our observation is about 2.79, whereas the densi of the earth as a whole is 5.52; obviously we should assume that the m terial of the interior must be of much greater density than that of the out part.

In order to explain available facts it is the accepted mode of procedu in science to propose an hypothesis; in some cases, like the present, t hypothesis cannot be tested experimentally or by direct observatio Any hypothesis concerning the interior of the earth will always be a spec lative hypothesis. But the scientific method demands that even a spec lative hypothesis should account in a satisfactory manner for all the ava able facts. This, then, becomes the criterion in choosing between seve speculative hypotheses advanced to explain a particular set of facts. the present problem, the easiest explanation fails to satisfy this criteri this is to assume that the earth was once a molten mass, and that by cooli it formed slowly an outer solid crust; and since it is liquid in the inter and loses heat by radiation, we could reasonably assume further that crust shrinks and develops cracks through which the hot liquid rock of interior is squeezed to the surface, furnishing spectacular evidence of molten condition of the earth in the past. Though this assumption see at first sight to fit with the known facts about volcanoes and geysers fails to account for a number of other facts. Before giving the mod conception of the composition of the earth, we should enumerate the fa that any hypothesis should be able to explain. This list need not memorized: it is presented merely for reference and to throw light on subsequent discussion.

1. The composition of the outer ten miles of the lithosphere is considered to be fairly well known from the boring of wells which have gone to a depth of more than two miles and from the work of erosion which has laid bare rocks that were once buried five to ten miles. The approximate composition is given in Table 18.

Table 18. Composition of the Outer Ten Miles of the Lithosphere

Igneous rocks	95.0%
Shales	4.0%
Sandstones	0.75%
Limestones	0.24%
All other deposits nearly	0.01%

This table shows that igneous rocks are by far the most abundant, and that man's most prized materials — soil, salt, coal, and others — are quantitatively insignificant. As mentioned above, the average density of the rocks found in the outer ten miles is 2.79, but the average density of the earth as a whole is 5.52, definitely indicating a heavier core within. If the average density is 5.52, the core must have a density of 7.8.

2. Hot lavas are constantly ejected from volcanoes. The magma comes up from below — from what depth is not known. The average temperature of lava is 1100° to 1200° C. Most of the lavas are basaltic. Deep holes bored in various parts of the world show an increase of temperature with depth. The deepest are four kilometers in depth. The average increase is 1° for every thirty meters (1° F. for every sixty feet). Hence, at a depth of a hundred kilometers (sixty miles) the temperature will be over 3000° C., far above the melting point of the rocks.

3. The overlying rocks exert pressure upon the rocks on which they rest. This pressure becomes tremendous with increasing depth: it has been calculated that at a depth of a hundred kilometers the pressure is about twenty-seven thousand atmospheres, or four hundred thousand pounds per square inch.

4. Evidence from the propagation of earthquake waves through the earth indicates that the composition of the earth changes with increasing depth. The long surface earthquake waves which travel around the earth beneath the surface rocks at two miles per second, proceed faster in ocean floors. The San Francisco earthquake was recorded in Japan before it was in New York; hence the floor of the oceans is of denser material, since the rate at which waves travel depends on the density and elasticity of the medium. The continents are made of granite and sedimentary rocks. Most lavas are basaltic, and basalt is quite dense. This suggests that at great depths the basalt or other denser material predominates. The primary (longitudinal) and secondary (transverse) earthquake waves pass through the outer eighteen hundred miles of the earth at a speed increasing with depth. This indicates, first, that this part is not fluid, but solid, since transverse waves do not travel through liquids, and second, that the increased speed is due to the increased rigidity (greater elasticity) of the rocks. The increased rigidity is due to the terrific pressure from above. After eighteen hundred miles, the secondary waves do not pass, and the speed of the

primary diminishes to one-half. Hence there must be a change in compos tion, and the inner core must be of different material.

5. The composition of the earth must be related to the other matter tha exists in the solar system. Although this statement at first sight may see purely dogmatic, there is evidence that supports it. In the first place, as shown in Chapter 18, the elements found in the sun are not different fro those found on earth. In the second place, the earth is constantly pelte from outer space by small bodies of matter existing in the solar system an related, it is reasonable to assume, to its members. When they enter th earth's atmosphere, these small bodies become heated by friction and b come incandescent. They are commonly called shooting stars, and a known scientifically as *meteorites*. Although some meteorites are of stor composition, a large number contain a core of iron and nickel, metals whic are not common on the earth's surface. The density of this core is abo 7.8, which is the same as that calculated for the earth's core.

Consideration of the above facts will show that there are a number th cannot be well accounted for by the molten-interior hypothesis. F example, the transmission of secondary seismic waves through the out eighteen hundred miles of the sphere is difficult to be accounted for if t interior is fluid, because transverse waves do not travel through liquid Further, if we assume a fluid interior and then consider the pressure of t overlying rocks, we shall arrive at the conclusion that the pressure w turn the fluid into a solid. For example, lead melts at 327° C., but if pressure of two thousand atmospheres is applied, lead can be heated 340° C. and still be solid. The modern conception of the composition the earth regards it as essentially rigid to the core, although it qui probably may once have passed through a molten condition. From t evidence of meteorites and the calculated density of the core of the ear it is inferred that the central part is composed of iron and nickel. T core is assumed to have a radius of nearly two thousand miles. Since t propagation of earthquake waves indicates a change in composition eight hundred and at eighteen hundred miles from the surface, it is reas able to assume that when the earth was in its molten condition the heav metallic core settled towards the center and the other materials underw a similar progressive rearrangement according to density, with the ligh material at the surface. The outer veneer is composed of sedimenta rocks to a depth of one to two miles. In many places the sedimenta rocks have been eroded and granitic masses are exposed. The shell fr two miles down to about forty miles is essentially granitic. Below fo miles (thirty to fifty kilometers) the rigidity increases rapidly as the r of earthquake waves increases up to eight hundred miles, and then it dr off somewhat until it reaches the core. Therefore it is assumed that composition changes to basic dense rocks. The next thousand miles (fr eight hundred to eighteen hundred) down to the core within is assun to be composed of a mixture of iron and nickel compounds. The c

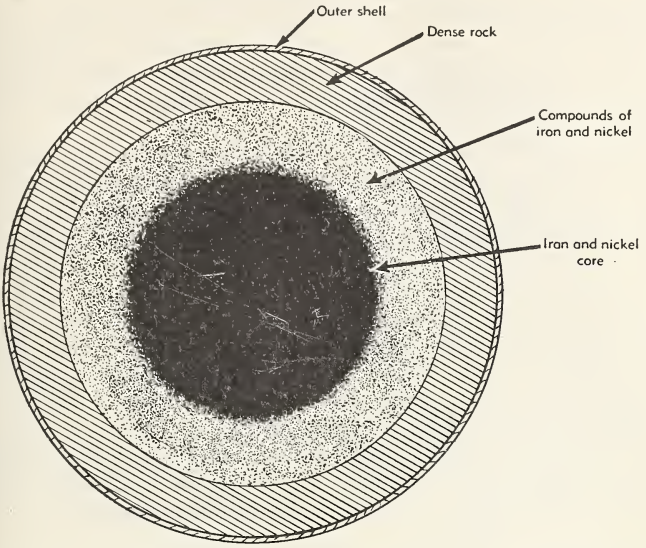


FIGURE 141. DIAGRAM SHOWING THE COMPOSITION OF THE EARTH'S INTERIOR

ving a radius of nearly two thousand miles, is assumed to consist of n and nickel, like most meteorites. This hypothetical composition is own diagrammatically in Figure 141.

igin and Movement of Magma

From the preceding discussion it follows that diastrophic and volcanic ivity are closely related. The temperature increases with depth, partly cause of pressure and partly because of the heat liberated by the changes radioactive minerals. These minerals contain such elements as uranium, lium, and thorium, which undergo spontaneous transformations to ier elements and give off heat; these changes are discussed in some detail Chapter 25. Therefore, the rocks at depths of thirty or forty miles are ated above their melting point, but remain in a solid condition because pressure from above. It follows that if the pressure is diminished, the k will often change into magma. The crustal adjustments which re- t in extensive folds and fractures initiate the formation and rise of gma. Let us assume that as a result of folding and fracturing (fault-) a fissure develops, extending to a depth of thirty to forty miles. The ssure along the fracture naturally diminishes, and consequently the saltic substrata, which are far above their melting point and kept in the

solid state only through the great pressure from above, liquefy. Now, t change of solid rock to fluid magma is accompanied by a slight drop density. In other words, the liquid magma occupies a greater space, a hence it is lighter than the adjoining rock; therefore it begins to rise u wards.

In this manner the magma may work its way up along the fissures a form dikes, sills, laccoliths, or batholiths, or it may reach the surface a cause an eruption. Gases accumulate from the chemical changes in t magma, and when sedimentary rocks along the fissures become fluxed, th melt, thus increasing the magma. For example, limestone, when it b comes fluxed in this manner, breaks up into lime and carbon dioxide, a the latter is held in solution by the magma because of the pressure, mu in the same manner as a "pop" bottle holds carbon dioxide in soluti The water vapor which is the chief constituent of the magmatic ga is assumed to originate partly from chemical reactions in the formati of magma and partly from entrapped water. Sometimes the magma water vapor may be derived from ground water with which the magm comes in contact near the surface. Depending on the pressure develop by the magmatic gases, the eruption may be quiet or explosive.

The Rock Cycle

The movement of magma performs another function in that it co pletes the rock cycle. Thus far we have seen that by the various eros agents all rocks are weathered and that they are transported eventu to a shallow sea and deposited as *sedimentary rocks*. Weathering, erosi and deposition tend to change all rock to the sedimentary type. during crustal movements, either igneous or sedimentary rocks which in the outer veneer of the earth's crust are caught within the folds or fr tures and are distorted and squeezed into *metamorphic rocks*. Finally the magma rises to the surface it forms large chambers and fluxes the joining rocks. The sedimentary, igneous, or metamorphic rocks wh adjoin the large magma chambers become fluxed and thus revert to original material from which they were formed, namely *magma*. T cycle is shown diagrammatically in Figure 142. Through the forces gradation, all three types of rocks, as indicated by arrows, give rise unconsolidated sediments which, on deposition, give sedimentary rocks shales, limestones, and sandstones. Both igneous and sedimentary ro when acted on by the forces of diastrophism are indicated as giving ris metamorphic rocks — gneisses, schists, quartzites and others. All th types of rocks when acted on by the forces of volcanism become flu and form magma, which rises upwards and upon solidification fo igneous rocks — granites, rhyolites, andesites, gabbros and other extru and intrusive rocks — which if they reach the surface will be eroded deposited as sedimentary rocks. Thus the cycle is completed, only start anew.

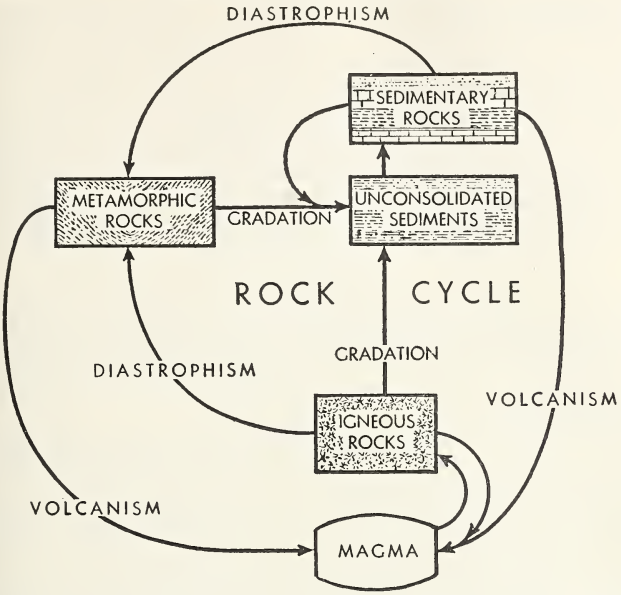


FIGURE 142. THE ROCK CYCLE
Courses followed in the evolution of rocks

Our consideration of the rock cycle completes the study of the gross anges occurring over the face of the earth: the changes of atmospheric essure and of temperature; the blowing of the winds; the changes brought out by water on surface and subsurface; the mighty changes which built ountains and gave rise to rivers of molten lava; and finally, the changes elements to form compounds. During this study, a number of prinples were introduced in a qualitative manner. For example, the expanon of gases and liquids when heated, the increase of the rigidity of solids ith increase of pressure, and the combination of elements in definite tios by weight. Finally, as a summary, a very general principle may be rived from the study made thus far, namely, that *the tendency of the anges studied is toward a system of greater stability.* The waters of the rth tend to reach the sea level, whence they cannot fall to a lower level. ocks caught in folds of faults rearrange toward denser materials in order occupy a smaller volume, and their crystals rearrange in such manner to offer the least resistance to pressure. Rocks when crystallized from agma achieve characteristic structures which are the most stable in their rticular environment. Similarly, in the few chemical changes that were udied it was found that they tend to proceed in the direction that can

produce the most stable system of substances. Other observations indi cate that this is a general trend in many changes occurring in nature — trend to pass from the least stable to the most stable condition.

The study of principles thus far has been made in a qualitative manner Quantitative data and mathematical calculations were mostly avoided in order to give the student an opportunity to obtain a bird's-eye view of large number of changes before attempting to isolate certain importan changes and to study them in detail. The first of these, discussed in th next chapter, is the concept of motion and force, the *agent of change.*

SUMMARY

1. Volcanism includes all the movements of molten rock and is the most impor tant constructive force building up the structural elements of the earth.
2. A volcano is an opening through which gases, molten rock, and solid roc fragments are ejected.
3. The ejection of hot materials from a volcano may be of the quiet type, emi ting lava, the violent explosive type, ejecting mostly ashes and gases, or a intermediate type between the two.
4. Volcanoes usually build conelike structures; the shape of the cone depen on the type of ejected material.
5. The products of volcanic ejections are gases, fragmental material, and lav
6. Volcanic gases consist mostly of water vapor; gases of sulfur and other po sonous gases, however, are usually found among volcanic gases. The fra mental material varies in size from large rocks to fine dust.
7. Different volcanoes erupt lavas of different kinds. Most lavas are of basalt composition — that is, they contain a preponderance of ferromagnesia minerals.
8. Lavas containing large amounts of gases may form porous volcanic scoria froth-like pumice.
9. Magma which solidifies without reaching the surface forms batholiths, dike sills, and laccoliths; the names of these intrusive bodies are related to the shape.
10. The intrusive igneous rocks have a coarse texture; the extrusive igneou rocks have a fine texture; a glassy rock forms when crystallization is rap if the amount of silica is high.
11. The various types of igneous rocks are: granites, rhyolites, diorites, a desites, gabbros, basalts, obsidians, and volcanic breccias and tuffs.
12. The distribution of active volcanoes follows closely the earthquake zones an the most recent rugged mountain systems.
13. The interior of the earth is inferred from a large number of facts. It has a iron-nickel core with the denser rocks towards the inner core and the light rocks towards the surface.
14. The origin and movement of magma is believed to be related to (*a*) intern heat of the earth from radioactive changes, (*b*) pressure of the overlyi

rocks, (*c*) release of pressure along fractures caused by diastrophic movements.

. In the changes which have been studied, a complete rock cycle is discernible.

STUDY EXERCISES

. Make a rough diagram showing the following intrusions and extrusions:

dike	sill	volcanic neck
laccolith	lava flow	cinder cone
batholith	magma chamber	composite cone

Indicate the type of rocks which are likely to be encountered in each.

. Write "D" if the following are caused by diastrophic changes; "V" if by volcanic changes; "G" if by gradational changes. More than one cause may be involved.

.... shale	.... mica	.... gneiss
.... marble	.... obsidian	.... limestone beds
.... slate	.... ripple marks on top of a hill	.... schistose structure
.... pumice stone		

. Make a diagram of the rock cycle as appears on page 213 of the text but greatly enlarged to include the following: (*a*) all the various types of metamorphic, sedimentary, and igneous rocks that we have studied (list these under each section); (*b*) the kind of unconsolidated sediments. Briefly explain the rock cycle, the formation of magma, the rise of magma, the composition of the outer and inner shells of the earth, the degradation of rocks and transportation of sediments and their consolidation into sedimentary rocks, and finally the crustal movements which gave rise to metamorphic rocks.

. Review the evidence for the composition of the earth and the explanation of magma formation and movements. Make a table in which you contrast two of the hypotheses proposed.

Evidence	Hypothesis No. 1 Statement of Hypothesis	Hypothesis No. 2 Statement of Hypothesis

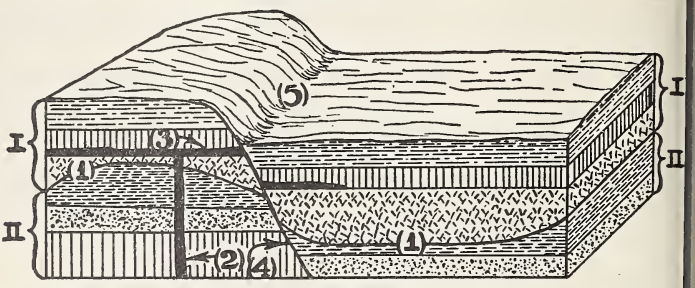
. By referring to the diagram on page 216, select the given alternative that correctly completes each of these statements:

The symbol *II* stands for (*a*) layers of igneous rock; (*b*) layers of sedimentary rock; (*c*) an anticline; (*d*) a syncline; (*e*) a batholith. .....

The strata represented by *II* were originally (*a*) the result of volcanic activity; (*b*) the result of diastrophism; (*c*) deposited below sea level; (*d*) an unconformity; (*e*) the result of glacial action. .....

The strata represented by *II* were elevated because of (*a*) erosion; (*b*) sedimentation; (*c*) weathering; (*d*) diastrophism; (*e*) faulting. .....

After elevation the erosion of the strata represented by *II* resulted in the



formation of (*1*), now known as (*a*) a thrust fault; (*b*) a tension fault; (*c*) syncline; (*d*) an anticline; (*e*) an unconformity. .....

The erosion resulting in (*1*) was followed most immediately by (*a*) subsi ence and inundation; (*b*) volcanic activity; (*c*) penetration of igneous m terial; (*d*) sedimentation; (*e*) faulting. .....

The next stage was (*a*) faulting; (*b*) sedimentation; (*c*) erosion; (*d*) intrusi of igneous material; (*e*) glaciation. .....

The next stage was (*a*) faulting; (*b*) sedimentation; (*c*) erosion; (*d*) an u lifting of the region; (*e*) subsidence and inundation; (*f*) glaciation. .....

The next stage was (*a*) faulting; (*b*) intrusion of igneous material; (*c*) gla ation; (*d*) sedimentation; (*e*) subsidence. .....

The next stage was (*a*) faulting; (*b*) intrusion of igneous material; (*c*) gla ation; (*d*) sedimentation; (*e*) metamorphosis.

The symbol (2) represents a (*a*) batholith; (*b*) laccolith; (*c*) sill; (*d*) dik (*e*) fault. .....

The symbol (3) represents a (*a*) laccolith; (*b*) batholith; (*c*) sill; (*d*) strik (*e*) dip. .....

The symbol (4) represents (*a*) a tension fault; (*b*) a thrust fault; (*c*) a strik (*d*) an unconformity; (*e*) a batholith. .....

The symbol (5) stands for (*a*) an unconformity; (*b*) a dip; (*c*) a strike; (*d*) scarp; (*e*) an anticline. .....

6. Indicate the chief volcanic zones. Show their relation to earthquake zon name one or two important volcanoes in each zone.
7. Discuss the importance of volcanism to the economic resources of the Unit States.

FOR FURTHER READING

1. Croneis, C., and W. C. Krumbein, *Down to Earth.*
Volcanic eruptions are discussed in Chapter 20, intrusive and extrusive ro in Chapters 21–22, and the interior of the earth in Chapter 19.
2. Longwell, C. R., A. Knopf, and R. F. Flint, *Outlines of Physical Geolo*
Volcanic eruptions are discussed in Chapter 12, intrusive and extrusive ro in Chapter 13; similarly the interior of the earth is discussed in Chapter 14.
3. Agar, W. M., R. F. Flint, and C. R. Longwell, *Geology from Origi Sources.*
Descriptive stories on volcanic eruptions will be found in Chapter 11.

11

Motion and Force

s one considers the events described in the previous chapters it becomes ıcreasingly evident that nothing is static or permanent. All things appear ɔ be moving or growing or disintegrating or changing in some way. The ırth rotates and revolves, always with such regularity that these motions ɛrve as both clock and calendar. On the surface of the earth various agen- es carry on their work of disintegrating rock and transporting the result- ıg fragments or solutions to lower levels. Counter to these leveling-off rocesses are others which tend to lift portions of the earth's surface and wer other areas. In addition to these large-scale crustal changes, which ɛ easily observed and which for the most part are physical, there are other ıanges in which substances are drastically modified to form other kinds matter and to release or absorb energy. In the midst of all these events, ving things grow, reproduce, die, and decay.

One who would understand and interpret even some of the simpler ıenomena of nature must be on the alert to avoid either of two common rors. The first is to oversimplify, a temptation that often has led to ulty interpretations. The sun rises and sets; the simplest and most ap- ıarent explanation was that the sun moved around the earth in a circular ıth. The second error is to assume an overcomplexity or lack of order. onfronted by a maze of natural events, many of which are not yet fully ıderstood, one might conclude that nature is chaotic and confusing and ıat no natural law exists.

It is therefore necessary to start with simple events and to build up a ıowledge and understanding of certain fundamental concepts and prin- ɔles. The first of these is *motion*; the second is that which produces ange in motion — *force.*

MOTION

A body in motion is constantly changing its position relatively to some her object serving as a point of reference. Motion is therefore definable ly with reference to something else and is always *relative.* It would not possible, for example, to determine whether or not a lone body isolated

in space is in motion. The motion of a distant star is detected only as i slowly changes its position with reference to its neighbors. A car parke on the street is at rest relatively to the trees, the houses, and all object fixed on this planet, but in motion with respect to the sun and other as tronomical bodies.

Motion appears in all natural events and human activities. Sitting i a quiet room, one may be totally unable to perceive any motion. Yet i the air there are thought to be multitudes of very small particles which ar called molecules and which are moving with the speed of a rifle bulle Even in the solid material of the walls or the furniture these teeming pa ticles are in a constant state of motion. The light which streams from th lamp is produced by the rapid vibrations of even more tiny particles withi the atoms of the lamp filament. At the power plant which furnishes th electricity for the lamp, huge machines are rapidly rotating. Motion the very essence of the many forms of energy, including heat, light, soun and electricity. Everything, large and small, moves; but it is the motio of gross, visible objects that one can best observe, and such were the m tions first studied by scientists. The motions of the earth, of the planet of a thrown ball, or of objects dropped from a height, all invited invest gations and study which have been very fruitful. The laws of mechani resulting from such studies are applicable to all bodies, whether planets molecules, and are the basis upon which the physical sciences have be built.

Uniform Motion

The actual motions ordinarily observed, like those of an automobile of a rifle bullet, are very complex. It is therefore best to start with th very simplest case. Imagine an automobile driven very carefully an steadily along a perfectly smooth and straight road so that in each sma fraction of time (for example, a second) it moves the same distance as i each preceding fraction of time. Such motion, although seldom observe in nature, is *uniform*. The distance covered in a given direction in one un of time is known as *velocity*. In uniform motion the velocity is therefo unchanging, or constant.

If the steady automobile driver travels on the straight road a distance two hundred and twenty feet in five seconds, the velocity for the trip forty-four feet per second or thirty miles per hour. This simple proble

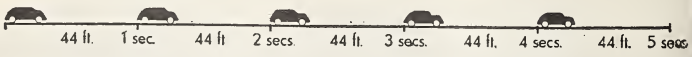


FIGURE 143. ILLUSTRATING UNIFORM MOTION

The velocity remains unchanged (constant velocity), equal distances being traversed equal intervals of time.

nd all others like it, may be represented by a general mathematical ex-
ression. Since velocity is the time *rate* of change of distance from a fixed
oint, it may be found by dividing that distance by the time required to
ɔver the distance.

$$v(\text{elocity}) = \frac{d(\text{istance})}{t(\text{ime})} \quad \text{or} \quad v = \frac{d}{t} \qquad \text{(Equation 1)}$$

The time rate of change of any quantity is always the amount of change
ivided by the time required to make the change. An expression of this
ind may be used to calculate any one of the quantities if the others are
nown. Thus:

$$d(\text{istance}) = v(\text{elocity}) \times t(\text{ime})$$

$$\textit{and } t(\text{ime}) = \frac{d(\text{istance})}{v(\text{elocity})}$$

There is no special name given to the unit of velocity. It is a derived
ıit having the dimensions

$$\frac{\text{length}}{\text{time}}$$

ıd is therefore expressed in terms of two of the three fundamental units
ɔage 23) — or multiples or fractions thereof — as: meters per second,
iles per hour, feet per minute, etc., depending on the system of measure-
ent being used.

While the terms velocity and speed are commonly used interchangeably,
ıch has an exact meaning for the scientist. Speed implies only the dis-
ınce covered in one unit of time, and since it expresses only magnitude, it
known as a *scalar* quantity. The population of the United States and the
ice of wheat are also scalar quantities. Velocity is the distance covered
ɛr unit of time in a given direction and therefore implies not only magni-
ıde but also direction. Such a quantity is known as a *vector* and is repre-
nted by an arrow whose length indicates to scale the magnitude and whose
p points the direction. Two cars, each moving at the rate of fifty miles
ɛr hour, meet and pass on a boulevard. They have the same speed but
ɔt the same velocity, for they are moving in different directions. The
elocities may be represented in this way:

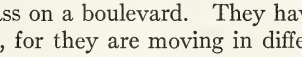


FIGURE 144. VECTORS REPRESENTING THE SAME SPEED, BUT DIFFERENT VELOCITIES

A traffic officer is actually reporting the velocity of a car if he cites the
rection as well as the rate at which it was moving. If he omits the direc-
ɔn, he is reporting only the speed. Such fine distinctions are not usually

required in everyday life but are quite useful and necessary in science. It is important to remember that every expression which includes velocity (v) represents a vector quantity.

Accelerated Motion

Most moving bodies constantly undergo changes in velocity. Their motion, which is said to be *accelerated*, may be best studied by example. Consider the motions of two cars, each starting from rest, or zero velocity. The driver in each car presses the gas feed or accelerator, and at the end of eleven seconds each car has attained a velocity of thirty miles per hour which is forty-four feet per second. An accurate timing device records the velocity of each car at the end of each of the eleven seconds.

A study of these data as recorded in Table 19 indicates that the first car moved irregularly. The increase of velocity in the first second was two feet per second; in the second, three feet per second; then one foot per second, three feet per second, and so on. The car was accelerated but in an irregular and nonuniform manner. Acceleration of this kind cannot be reduced to any simple mathematical formula and will not be considered in this text.

The second car moved steadily with a uniform increase in velocity for every second it was in motion. Its performance is an example of *uniform*

Table 19

Time Seconds	Velocity of Car No. 1 Feet per second	Velocity of Car No. 2 Feet per second
1	2	4
2	5	8
3	6	12
4	9	16
5	15	20
6	20	24
7	24	28
8	30	32
9	35	36
10	40	40
11	44	44

accelerated motion, which merits a detailed discussion both in this chapter and in a later chapter in connection with gravity. For such motion the relationships between the various factors — time, distance, velocity, and acceleration — may be reduced to simple mathematical expressions. The term *acceleration* means time *rate of change of velocity*. Since any rate of change is the change divided by the time required,

$$\text{acceleration} = \frac{\text{change in velocity}}{\text{time required}}$$

n other words, it is *the change in velocity in one unit of time.* Since only ıose cases are considered in which a body is initially at rest, the change in elocity ($v_{\text{final}} - v_{\text{initial}}$) is simply the final velocity attained, for the initial elocity is zero. Hence,

$$a = \frac{v_{\text{final}}}{t}$$

ıd final velocity, $v = at$ (EQUATION 2)

he acceleration for the second car may be obtained simply by noting that ıe change in velocity was four feet per second in one second. Or, by use the equation,

$$a = \frac{44 \text{ feet per second}}{11 \text{ seconds}}$$

$$= 4 \text{ feet per second per second}$$

(change in velocity, in this time unit)

he unit of acceleration therefore has the dimensions $\frac{\text{length}}{(\text{time})^2}$. Although is customary to use the same unit of time, appearing twice in the above xpression, the meaning of acceleration is better understood if two different me units are used. For example, using the same data for Car No. 2 (see able 19),

$$a = \frac{30 \text{ miles per hour}}{11 \text{ seconds}} = 2\tfrac{8}{11} \text{ miles per hour per second}$$

hich means that the change in velocity taking place every second is $\frac{8}{11}$ miles per hour. In the examples just studied the velocity increases ith the time and the acceleration is therefore *positive.* If the driver pplies the brakes in such a way that exactly the reverse process takes lace, the acceleration is *negative.*

alculation of Distance for Accelerated Motion

The next question is, How far does a uniformly accelerated body travel a stated time? For uniform motion the problem is simple with the elp of one version of Equation 1 on page 219: distance = velocity × time. his simplicity may be extended to accelerated motion if average veloc- y is used. The car which starts from zero velocity and moves with uni- rm acceleration, eleven seconds later attains a velocity of forty-four feet er second, with an average velocity of twenty-two feet per second. The verage velocity for all cases of uniform acceleration is one half of the ım of the initial and final velocities:

$$_{\text{verage}} = \frac{v_{\text{final}} + v_{\text{initial}}}{2} = \frac{44 \text{ ft per sec} + 0 \text{ ft per sec}}{2} = 22 \text{ ft per sec}$$

ıd $d = v_{\text{average}} \times t = 22 \text{ ft per sec} \times 11 \text{ sec} = 242 \text{ feet.}$

Though the acceleration was not used in this calculation, it may be incorporated in the equation for distance by a simple substitution. From Equation 2 on page 221,

$$v_{\text{final}} = at$$

Therefore,

$$v_{\text{average}} = \frac{v_{\text{final}}}{2} = \frac{at}{2}$$

and substituting $\frac{at}{2}$ for v_{average} in the equation for distance,

$$d = \frac{at}{2}\,t = \tfrac{1}{2}\,at^2 \qquad \text{(EQUATION 3)}$$

This is a fundamental equation for the uniformly accelerated motion of a body which starts from rest. Now, we test the equation by making the same calculation as above. The car moves from rest with an acceleration of four feet per second per second for eleven seconds:

$$d = \tfrac{1}{2} \times 4 \text{ feet per second per second} \times (11 \text{ seconds})^2$$

$$= 242 \frac{\text{feet} \times \cancel{(\text{seconds})^2}}{\cancel{(\text{seconds})^2}} = 242 \text{ feet}$$

which is identical with the answer obtained above. It should be noted that when all the units are carried along in the calculation they may be combined or canceled to give the correct unit dimensions of the answer.

Equation 3 tells that the *distance* a uniformly accelerated body moves varies with the *square* of the time, i.e., $d \propto t^2$, since for a given case $\frac{1}{2}a$ is constant. In Figure 145, for instance, during the first ten seconds the car should therefore move four times the distance it moves during the first five seconds, since

$$d = \tfrac{1}{2} \times 4 \frac{\text{feet}}{(\text{second})^2} \times (10 \text{ seconds})^2 = 200 \text{ feet}$$

and

$$d = \tfrac{1}{2} \times 4 \frac{\text{feet}}{(\text{second})^2} \times (5 \text{ seconds})^2 = 50 \text{ feet.}$$

This principle is of value to automobile drivers. With perfectly uniform acceleration, it takes twice as long to attain a velocity of sixty miles per

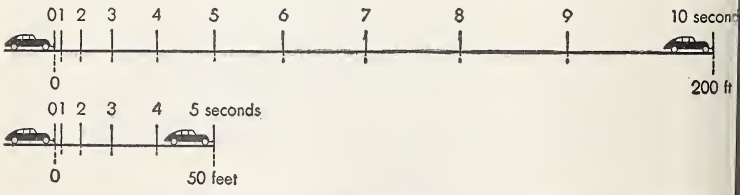


FIGURE 145. UNIFORM ACCELERATION

Distance varies with the square *of the time. Spaces show to scale total distance traversed by end of each successive second.*

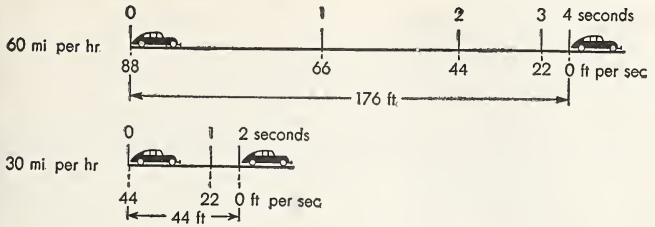


FIGURE 146. UNIFORM DECELERATION (UNDER IDEAL CONDITIONS)

The distance required to stop a moving car, after the brakes are applied, varies as the quare *of the velocity. The velocity at the end of each second is shown and the distance* aversed *during each second is indicated to scale.*

our as it does to attain a velocity of thirty miles per hour, and the car herefore moves four times as far in reaching the higher velocity. Of reater significance to our safety is the reverse process. Let us assume that he brakes are capable of giving the automobile a uniform deceleration or egative acceleration of twenty-two feet per second per second. When it s moving at a velocity of sixty miles per hour (eighty-eight feet per second), : can be brought to a stop in four seconds after the brakes are applied: t thirty miles per hour (forty-four feet per second), only two seconds are equired to bring it to a stop. In interpreting Figure 146, the distances raveled may be calculated:

$$d = \tfrac{1}{2} \times 22 \frac{\text{feet}}{(\text{second})^2} \times (4 \text{ seconds})^2 = 176 \text{ ft}$$

$$d = \tfrac{1}{2} \times 22 \frac{\text{feet}}{(\text{second})^2} \times (2 \text{ seconds})^2 = 44 \text{ ft}$$

our times the distance is therefore required to stop the car moving with wice the velocity. In general, the *distance* required to bring a moving ody to rest varies with the *square of the velocity.* But this is true only there is a uniform and constant decrease in the velocity.

FORCE

The study of motion suggests two questions. First, how may a body at est be put in motion, or, if it is in motion, how may its velocity be changed? Ve know from the preceding paragraphs that any change in the state of notion or of rest of a body means that an acceleration is imparted to it. Ve know from experience that such a change requires a continuous action r effort, which from now on will be designated as *force.* A force, therefore, s that which produces a change of motion or, better, imparts an accelera- ion to a body. But before a further consideration of force can be made, nother question must be answered and another concept introduced.

The "Natural State" of a Body

The second question is: What is the natural state of motion for a body that is, what does an object do when free of all forces?

Aristotle, who wrote so ably on scientific method and who urged re peated observation of natural phenomena, had made some observations o motion and had indulged in a considerable amount of speculation on th subject. He concluded that rest was the natural state of a body and tha moving bodies come to rest when the cause of the motion is removed. Thi idea prevailed for nearly two thousand years until Galileo and other coupled scientific experiment with scientific reasoning. Galileo conclude that once a velocity was imparted to a body, it continued to move in straight line with uniform velocity as long as no external forces came int play. Later, Newton incorporated this idea into his First Law of Motion

Every body continues in its state of rest or of uniform motion in a straight line unless it is compelled to change that state by a force.

Proof of the First Law of Motion

The proof of the first part of the law is quite apparent to any observe Bodies at rest (not in motion relatively to their surroundings) remain a rest. To move a body requires a force.

Experimental proof of the second part of the law presents difficulties Its proof, like its formulation, requires both scientific experiment and scien tific thought. A stone when thrown continues to move, but its motion not in a straight line nor is it uniform, and soon the stone comes to rest If we accept the idea of Aristotle that rest is the "natural state" of a body then the problem is to explain why the stone continues to move at all afte the force exerted by the thrower ceases. If, on the other hand, we accep as a working hypothesis the ideas of Galileo and Newton as expressed in th First Law of Motion, then whatever brings the body to rest must be found and ways to eliminate it from experiment must be sought. The main in fluence instrumental in arresting the flight of the stone is the force of at traction exerted by the earth (see next chapter).

The best we can do, then, in the next experiment is to keep this forc constant and to limit its effect as much as possible. To do this, the spher cal body whose motion we are studying is rolled along a smooth horizonta plane. After a push the ball rolls some distance before stopping. It can not curve toward the earth because of the surface on which it rests, but does not deviate to the right or left from a straight path. The attractio of the earth still brings it to rest, by pulling it against the surface an thereby creating friction. Both the ball and the surface having been mad smoother by polishing, again a push (the same amount of push each time is given to the sphere. This time it rolls longer and farther and with a les

apid decrease in velocity. The polishing and smoothing of the object is ontinued, and with each succeeding trial the sphere rolls farther and arther as the friction is diminished. As we know, friction cannot be en- irely eliminated, but the results f these experiments indicate that odies continue to move uniformly a straight line. Complete proof y this experimental method would equire complete isolation of the ody in space, which obviously is ot possible.

FIGURE 147. BALANCED FORCES

If just enough force, F, is applied to the moving cart to equal the retarding force F', due to friction and air resistance, the cart moves on uniformly (First Law of Motion).

On the other hand, if just enough rce to counterbalance the friction applied in the direction of the otion of the ball, it continues to ove uniformly. Here balanced rces are in operation. Their mbined effect is zero, yet the ball rolls on. One experiences the same henomenon in pushing a small cart (Figure 147). To start the cart—that , to give it an acceleration — requires force. But once it is in motion, ly a small fraction of the original force is required to balance the effects friction and air resistance and to keep it moving uniformly and in a raight line.

ertia and Mass

The First Law of Motion describes a fundamental property of matter, amely, *inertia* (page 121). Inertia is the resistance offered by a body to y change of motion. The amount of such resistance or inertia depends pon the quantity of matter in the body, or its *mass*. The mass of the dy, which is the measure of its inertia, is an invariable quantity: it re- ains constant regardless of the body's position and of the circumstances nder which it is measured. The mass is usually determined by balancing against another object whose mass is already known. The analytical alance (Figure 148) which one commonly sees in a physics or chemistry boratory is so used. The known masses are called "weights" and have een carefully calibrated by comparison with the standard kilogram and s fractions which are preserved in the Bureau of Standards.

leasurement of Force

A mathematical expression, if understood, shows clearly and effectively ow a force is measured and how it may be calculated. Since a force in it- lf is not a tangible thing and manifests itself only by its action on a body, measure of that action, that is, of the acceleration imparted to a given ass, gives both the amount of the force and its dimensions. For example,

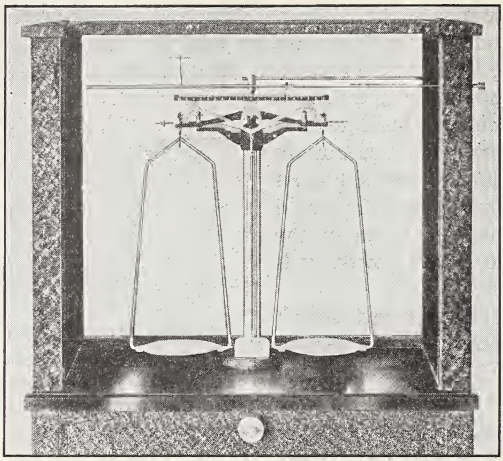


FIGURE 148

The analytical balance is used to determine the mass of a body or sample of materi which is balanced against known masses or weights. (Courtesy of the Wilkens Anders Company)

a force applied to a body of mass m gives the body an acceleration a a long as the force is applied. The quantity of force F depends upon the tw factors m and a. That fact may be expressed mathematically: F(orc $\propto m$(ass) $\times a$(cceleration).

$$F \propto ma$$

In order to change a proportionality of this kind into an equality it is cu tomary to insert a constant. However, if the proper units are selecte this constant becomes unity and then the equation for force is

$$F = ma \qquad \text{(Equation}$$

This fundamental equation may be used to arrive at some significa conclusions which clarify the relationship between the three quantities i volved. Suppose that different forces are applied to an object at differe times and on each occasion impart to it an acceleration. For these cas the mass is a constant; hence the acceleration in each case is proportion to the force applied. For example, the driver who successively has h automobile move with accelerations of three, six, and nine feet per seco per second really causes the engine to exert successive forces which are the ratio of 1:2:3. This relationship is shown in Figure 149, where for and acceleration are represented by vectors.

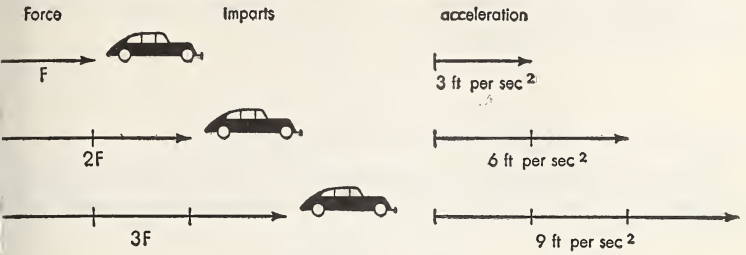


FIGURE 149. THE ACCELERATION IMPARTED TO A BODY IS IN DIRECT PROPORTION TO THE FORCE APPLIED

he Second Law of Motion

The relationship expressed in the equation, $F = ma$, was formulated by Newton as the Second Law of Motion. This law may be stated thus:

The acceleration imparted to a body is proportional to the force acting and akes place in the same direction as the force applied.

On the other hand, if identical forces are applied to two different masses, he greater acceleration will be given to the smaller mass. For example, a nan exerting his full force may give to a stalled light car an acceleration of).5 feet per second per second. Applying the same force to a heavier type of car which has twice the mass of the lighter one, he is able to impart only ne half as much acceleration, or 0.25 feet per second per second. In Figure 150 the accelerations are represented by vectors (arrows). It is his principle that is utilized in the determination of mass by the inertia alance. Identical forces are used, accelerations are measured, and the nass or inertia of one of the bodies is calculated relatively to the other, vhich is a standard mass.

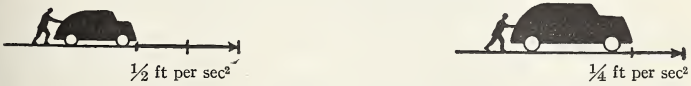


FIGURE 150. ACCELERATION VARIES INVERSELY AS THE MASS IF THE FORCE IS CONSTANT

The smaller the mass the greater the acceleration

Units of Force

The units of force are defined in terms of the simplest possible fundamental units. The absolute or invariable unit which is employed throughout this text may be described as that force which gives to one unit of mass

an acceleration of one unit of length per second per second. The dimensions of the absolute unit of force are, therefore,

$$\frac{\text{mass} \times \text{length}}{(\text{time})^2}$$

Specifically, two different units are in use:

The *metric unit* is that force which gives to a mass of one gram an acceleration of one centimeter per second per second; in terms of the fundamental units it is

$$\frac{\text{gram} \times \text{centimeter}}{(\text{second})^2}$$

and, as this is a rather long title, it is given the shorter name *dyne.*

The *British unit* is similarly that force which imparts to a pound mass an acceleration of one foot per second per second, or

$$\frac{\text{pound} \times \text{foot}}{(\text{second})^2}$$

and it is given the name *poundal.*

Briefly, the units may be described as follows:

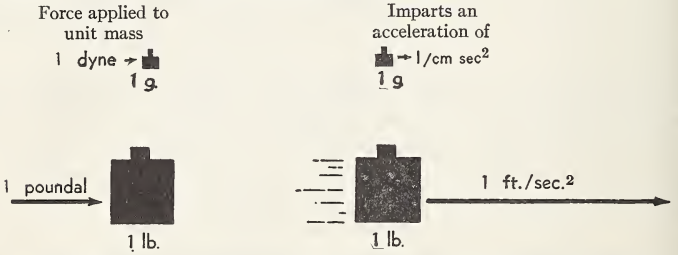


FIGURE 151. A COMPARISON OF THE DYNE AND THE POUNDAL

Unit forces involve unit masses (represented as solid cubes) and unit accelerations (represented as vectors).

Calculation of Force

Force, mass, and acceleration may each be calculated, provided the other two quantities are known, by use of Equation 4 on page 226. Let it be assumed that the same automobile that was given an acceleration of $2\frac{8}{11}$ miles per hour per second has a mass of three thousand pounds. What force is exerted by the engine? To solve, it is first necessary to change $2\frac{8}{11}$ miles per hour to feet per second, since the unit of force is in terms of feet per second per second.

$$\frac{2\frac{8}{11} \text{ mi/hr} \times 5280 \text{ ft/mi}}{3600 \text{ sec/hr}} = 4 \text{ ft/sec change in velocity every second.}$$

The acceleration is therefore 4 ft per sec per sec

$$F(\text{orce}) = m(\text{ass}) \times a(\text{cceleration})$$

Substituting,

$$F = 3000 \text{ lbs} \times 4 \text{ ft/sec}^2 = 12{,}000 \text{ lbs ft/sec}^2$$
$$= \textit{12,000 poundals}, \text{ the force required.}$$

A force of three hundred thousand dynes is applied to a small hand truck whose mass is fifty kilograms. What acceleration is given to the truck?

Since $$F = ma, \qquad a = \frac{F}{m}$$

and since $$50 \text{ kilograms} = 50{,}000 \text{ grams},$$

$$a = \frac{300{,}000 \text{ g cm/sec}^2}{50{,}000 \text{ g}} = 6 \text{ cm/sec}^2, \text{ the acceleration imparted.}$$

The Third Law of Motion

The first two Laws of Motion were based upon the experimental work of Galileo, and the First Law had, prior to Newton, been clarified by Descartes. The Third Law, however, was first formulated by Newton:

To every action there is always opposed an equal reaction; or, the mutual actions of two bodies on each other are always equal and opposite.

The words *action* and *reaction* here mean opposing forces; for forces always occur in pairs. If one pushes against a table, the table resists with an opposite and equal force. This is true even where the force is great enough to cause the table to move, but then the person pushing the table must have more traction against the floor than the table has. He pushes backward on the floor with his feet, and the floor pushes with an equal force — and man and table move forward. All self-propelled objects exert a force backward and are moved forward by the reaction; the pedestrian and the horse move through the force of their feet against the earth; the automobile and locomotive through drive wheels against the road and track; the steamship through its propeller against the water; and the airplane by its propeller against the air.

The driving force on the rear axle of an automobile tends to rotate the entire car in an opposite direction around that axle, but absorption of this reaction by the earth and the weight of the car more than offset this tendency. Some of the early tractors did at times turn completely over backwards around the rear, or driving, axle.

The rotating lawn sprinkler, the first steam engine (see Hero's, page 394), the jet propelled rocket or plane — all owe their motions to the reaction or recoil due to escaping fluids. When a gun is fired, the bullet leaves the muzzle with a high velocity; the gun, and the man holding the gun, or the

FIGURE 152. WILL THE FAN MOVE (A) OR (B)?

gun carriage, are propelled, or "kicked," backward with the same forc but, because of their greater mass, with less velocity. This recoil shock absorbed by the earth, and in theory the earth is also moved. The cent of gravity (center of mass) of the whole system — bullet, gun, and m (assuming the man absorbs all of the recoil) — does not change. Th recoil force is utilized in the operation of machine guns. The gun bar recoils against a spring which is distorted and by recovery operates t loading and firing mechanism.

Two simple experiments may further serve to illustrate the law. In small becalmed sailboat, a large electric fan (Figure 152) is placed so as blow against the sail. There is no motion of the boat. The action by t fan, which is on the boat, is against the sail, which is also a part of the bo This is of no more effect than is the push of one of the passengers agai the mast or sail, or the attempt to lift oneself by one's bootstraps. T fan is then turned around so as to blow to the rear of the boat, where th is no sail. The boat moves, for now there is reaction against something e ternal to the boat — the air.

A second experiment concerns two boys of different weight on ice skat roller skates, or small carts, any of which moves with little friction on uniform surface. The boys stand facing each other several feet apa and each holds to the end of a rope held taut between them (Figure 15

Boy *A* pulls sharply on the rope while Boy *B* holds it firmly. The bo

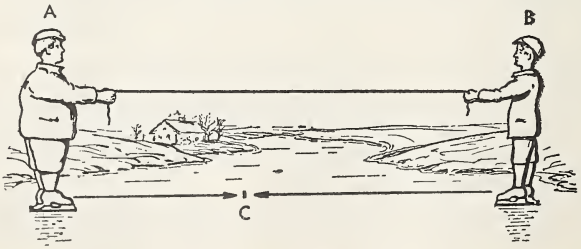


FIGURE 153. ACTION AND REACTION ARE EQUAL AND EQUAL MOMENTA ARE IMPARTED TO THE TWO BOYS

)proach each other and meet at a point C, which is carefully marked. hey resume their former positions and repeat the experiment, but this me B pulls the rope. They meet at the same point as before. In the next ial both pull simultaneously on the rope and with the same results.

Finally, it will be shown in Chapter 14 that the attraction between the .rth and the sun or between any two celestial bodies is mutual. The .rth attracts the sun, and the sun attracts the earth with an equal but)posite force. Thus there can be no push or pull on one body unless there a corresponding push or pull on another body.

omentum

A rifle bullet moving with a velocity of only a few feet per second would)t injure anyone it happened to strike, whereas the same bullet fired with high velocity from a rifle would be fatal. On the other hand, a hundred)und weight moving at even a slow rate would probably knock one over ıd cause injury. This combination of mass and velocity sometimes .lled quantity of motion, depending upon both of these quantities for its .lue, is known as *momentum* and is represented by the formula:

$$M(\text{omentum}) = m(\text{ass}) \times v(\text{elocity})$$
$$M = mv \qquad \text{(Equation 5)}$$

nce velocity, a vector quantity, appears in this formula, momentum is a rected, or vector, quantity. The relationship of this important concept force, acceleration, and the laws of motion is illustrated by the ex- riment with the boys which is described in the preceding section. The ro boys of unequal masses m and m_1 (Figure 153) are drawn together by e pull on the rope connecting them. The same force is, therefore, acting both. If the boys were of equal mass, they would be given equal ac- lerations when either one or both pulled on the rope. But since they e not equal, a greater acceleration is imparted to the one of smaller ass, m_1. In accordance with the second law of motion their accelera-)ns are inversely proportional to their respective masses.

Mathematically, $F = ma = m_1a_1$, where a is the acceleration of the hter and a_1 that of the heavier boy. At any instant during the action of e force the velocities attained are v and v_1 and since

$$a = \frac{v}{t} \text{ and } a_1 = \frac{v_1}{t_1},$$

$$\frac{mv}{t} = -\frac{m_1v_1}{t_1}$$

ıe force acts on both boys for the same length of time ($t = t_1$). Therefore,

$$mv = -m_1v_1$$

ıe boys have numerically equal momenta, but since the velocities are in

opposite directions, one momentum is negative to the other. Considerin the system as a whole, the total momentum is zero. After they mee both boys are at rest and the total momentum of the system is again zer

Law of Conservation of Momentum

The facts stated in the previous paragraph serve to illustrate the princ ple of conservation of momentum, which is deduced from the Laws of M tion and which may be experimentally verified. The principle may b stated as follows:

The total momentum of a system of bodies remains constant unless extern forces act upon it.

A lone body moving along a horizontal plane without friction undergo no change in velocity (First Law) and therefore no change in momentun If it were broken into several pieces by an internal explosion, its center gravity would continue to move as before, and the total momenta of th fragments would equal the momentum of the body before disintegratio

Where two or more bodies, moving independently, collide with ea other there is likewise a conservation of momentum. There are two typ of collision, each of which may be considered for two bodies.

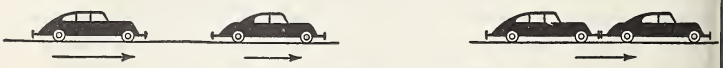


FIGURE 154. INELASTIC COLLISION
Upon impact the bodies remain together and move as one

The first type is *inelastic.* After collision the bodies remain together a continue to move as one. One automobile may collide with another mo ing in the same direction and, if their bumpers lock, both continue to mo as one body (Figure 154). The resulting velocity of the united bodies readily calculated by the equation:

$$\begin{array}{ccc} \text{(Before collision)} & & \text{(After collision)} \\ mv + m_1v_1 & = & (m + m_1)v_2 \end{array}$$

The second type is *elastic.* No actual bodies of experimental size a perfectly elastic, but some substances, like steel, have a very high el

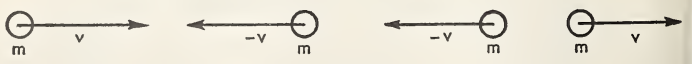


FIGURE 155. ILLUSTRATING ELASTIC COLLISION
Upon impact both bodies rebound, with the same difference in motion and with the same momentum as before.

city. If two elastic bodies of equal masses approach each other with equal eeds, their momenta are equal but opposite (Figure 155). As in the case the two carts, the total momentum of the system is zero. Upon collision ere is a brief force or reaction between them, and according to the Third aw this must be the same for each. After collision, however, they re- ound with equal speeds so that the total momentum remains at zero. The following equations represent the facts for the case of equal masses oving in opposite directions at equal speeds:

(Before collision)	(After collision)
$mv + (-mv) = o$	$-mv + mv = o$

here the masses are different, the larger mass may come to rest and the naller one rebound with greater velocity than before collision. In all ses of perfectly elastic impacts, not only is the momentum conserved but e relative velocities of the two bodies are the same after the impact as fore. Finally, the Law of Conservation of Momentum leads one to con- ude that there can be no immovable bodies and, conversely, that all rces are irresistible. We shall use this principle in the formulation of hypothesis on the origin of the solar system (Chapter 47).

SUMMARY

. *Motion*, which is change of position of a body relatively to some other body, is of two kinds:

(*a*) *Uniform*, in which the same distance is covered in equal successive units of time ($d = vt$). Distance varies with the time. *Velocity*, or rate of change of position, is a vector quantity. *Speed* is a scalar quantity.

(*b*) *Accelerated*, in which the velocity changes. *Uniform acceleration*, a special kind, is that in which the change in velocity is constant: $a = v/t$ for cases in which the initial velocity is zero. Distance varies with the square of the time: $d = \frac{1}{2} at^2$. The distance required to stop an object which is decelerated uniformly, varies as the square of the velocity.

. *Rest* like motion is a relative term. There is no such thing as absolute rest. Everything moves.

. A *vector* quantity is one which has both magnitude and direction. It is represented by a graphical arrow drawn in the appropriate direction and with a length proportional to the magnitude.

. *Force* causes change of motion, or acceleration: $F = ma$. The absolute units of force are the dyne (g cm/sec^2) and the poundal (lb ft/sec^2).

. *Mass*, the quantity of matter in a body, is invariable and is a measure of a body's *inertia* (or resistance to change of motion).

. *The Laws of Motion*, formulated by Newton, are:

(*a*) Bodies at rest remain at rest; bodies in motion continue to move uniformly in a straight line unless acted upon by some force.

(*b*) The acceleration imparted to a body is proportional to the force produ ing it and takes place in the direction in which the force acts.
(*c*) To every force there is an equal counter force.

7. *Momentum* is the product of mass × velocity. In any system consisting one or more bodies the total momentum is constant — resulting in the *co servation of momentum.* This rule holds for inelastic impacts, where the bo ies act as one after collision, and for elastic impacts, where no energy is lo by collision.

STUDY EXERCISES

1. For each term compose a concise word definition or statement, and supply mathematical expression or formula.
(*a*) Velocity. (*b*) Acceleration.
(*c*) Distance covered under uniform velocity.
(*d*) Distance covered under uniform acceleration.
(*e*) Force. (*f*) Momentum. (*g*) Mass.
2. In the table are given four examples of motion, *A*, *B*, *C*, and *D*, all of whi except *C* start from rest, with the velocities attained at the end of each se ond. Select for each the phrase below that classifies it.

Seconds	Velocity at end of given second (feet per second)			
	A	B	C	D
1	2	8	5	4
2	6	16	5	10
3	9	24	5	8
4	15	32	5	6
5	18	40	5	2

(*a*) Uniform motion. ....
(*b*) Accelerated motion. ....
(*c*) Non-uniformly accelerated motion. ....
(*d*) Uniformly accelerated motion. ....
(*e*) Motion resulting from a continually varying force. ....
(*f*) Motion resulting from a constant force continuously applied. ....
(*g*) Motion resulting from the application of balanced opposing forces after the initial motion is given. ....

3. An automobile travels north two hundred and forty miles in eight hours.
(*a*) Calculate the average velocity (show units).
(*b*) Express this velocity in feet per second.
(*c*) How many feet does it move, at this rate, in one minute?
(*d*) How long would it take to travel from Chicago to Cincinnati (three hu dred miles) at this average velocity?
4. A pursuit plane flies at a velocity of three hundred and sixty miles per ho
(*a*) How many feet per second is this?

(*b*) How many miles does it travel in one and a half hours assuming uniform velocity?

(*c*) In what time would it overtake another plane forty miles away flying in the same direction with a velocity of two hundred miles per hour?

. An explosion is heard ten seconds after the flash of it is seen. Sound travels at a velocity of 1150 feet per second under the existing conditions. Assuming that the light from the flash travels instantaneously, calculate the distance of the observer from the explosion.

. How long does it take light, with a velocity of 186,000 miles per second to travel from the sun to the earth 93,000,000 miles away?

. A plane before take-off attains a velocity of one hundred and eighty feet per second in ten seconds. Assuming a uniform increase in velocity calculate:

(*a*) the acceleration;

(*b*) the distance required for the take off.

. A body moving with uniform acceleration travels five centimeters in the first second.

(*a*) What is its acceleration?

(*b*) How long required for it to travel twenty meters?

(*c*) How far would it travel in ten seconds?

. A car starts from rest and under uniform acceleration travels two hundred feet in ten seconds.

(*a*) What is its acceleration?

(*b*) What velocity does it attain by the end of the ten seconds?

(*c*) How far would it travel in five seconds under the same acceleration?

. An automobile with a mass of three thousand pounds is brought to rest from a velocity of sixty miles per hour in eight seconds.

(*a*) What is the negative acceleration?

(*b*) What is the braking or retarding force required?

(*c*) What distance does it move as it is being brought to a stop?

(*d*) What distance would it move while being braked to a stop from a velocity of thirty miles per hour?

. An automobile weighing twenty-six hundred pounds is given a velocity of twenty feet per second in four seconds. Calculate the force exerted by the motor.

. A force of thirty-five thousand dynes is applied to a small cart having a mass of twenty kilograms. What acceleration is imparted to the cart?

. A ninety-five-pound shell is given a velocity of twenty-four hundred feet per second as it leaves the muzzle of the gun. It travels a distance of sixteen feet in the gun. Assuming a uniform acceleration in the gun:

(*a*) How long does it take the shell to leave the gun?

(*b*) What is the acceleration?

(*c*) What is the force exerted by the explosive?

. For each of the situations or phenomena described below determine which one of the laws of motion is illustrated.

(*a*) Bodies near the moon fall to it with less acceleration than those which fall to the earth.

(*b*) The engine of an automobile moving with uniform velocity exerts jus enough force to balance the retarding forces of friction and air resistanc

(*c*) If the valve on a high pressure gas cylinder is broken off, the cylinder propelled at high speed by the escaping gas.

(*d*) A steel ball bounces.

15. Make a chart something like this, in which uniform motion and accelerate motion are contrasted.

	Uniform Motion	Accelerated Moti
Formula for velocity		
Formula for distance		
Velocity is constant (check)		
Velocity varies with time		
Distance varies with time squared		
Distance varies with time		
Requires only balanced forces to continue		
Requires continuous force		

16. From the expression for the second Law of Motion show mathematica that:

(*a*) when identical forces are applied to two different bodies, the respecti accelerations imparted to the two bodies vary inversely as their mass

(*b*) when two different forces are applied to identical masses, the accele tions are directly proportional to the forces.

17. Is momentum a scalar or a vector quantity? With what velocity (ft/s must a hundred-pound shell move in order to have the same momentum a two-thousand-pound automobile moving with a velocity of thirty mi per hour?

18. Two identical automobiles moving with the same speed crash head on, bu as their bumpers become entangled, they do not rebound. What becomes their momenta?

19. In each statement find and briefly discuss the error:

(*a*) Nature is chaotic and confusing — neither order nor natural law exist

(*b*) "The natural state of a body is rest, and all bodies which are set in m tion come to rest." Aristotle.

(*c*) Traffic officer: "The car was moving with a velocity of sixty miles p hour."

(*d*) When a body in motion strikes an immovable body, momentum destroyed.

20. From the equation for uniform motion, $d = vt$, and that for uniformly acc erated motion, $v\ final = at$, derive the equation for distance for uniform accelerated motion starting from rest.

FOR FURTHER READING

1. Eyring, Carl F., *A Survey Course in Physics.* New York: Prentice-H Inc., 1945.

Chapter III deals with motion and force and gives a preview of some of material to follow — primarily for those who have had no training in scienc

. LEMON, HARVEY B., *From Galileo to the Nuclear Age.* Chicago: The University of Chicago Press, 1946.

Chapters 1, 2, 7, and 8 give a clear and entertaining discussion of the laws of motion and the principle of conservation of momentum. For the beginner.

. MOTT-SMITH, MORTON, *This Mechanical World.* New York: D. Appleton and Company, 1931.

Chapters VII, X, XI, and XV explain how some of the great principles of dynamics were developed — in a non-mathematical and lively style. For the student who seeks real understanding.

. TAYLOR, LLOYD WILLIAM, *Physics, the Pioneer Science.* Boston: Houghton Mifflin Company, 1941.

Chapters 1, 2, 10, and 11 contain a more thorough treatment and interpretation of the laws of motion and the rôle of mechanics with special attention to the evolution of the fundamental concepts.

. STEPHENSON, REGINALD J., *Exploring in Physics.* Chicago: The University of Chicago Press, 1935.

Chapters 1, 2, and 4 will help the student who has trouble with the mathematical problems. Principles are explained briefly but clearly, type problems are worked step by step, and there are more problems for the one who wishes to test his skill. Answers are given.

12

The Earth Attracts

IN THE PRECEDING CHAPTER it was shown that the action of a continuo and constant force on a body imparted to that body a uniformly accelerat motion. Muscular forces or those exerted by man-made machines serv to illustrate this discussion and to develop the concept of force and moti and the laws of motion. There is, however, another force in continuo operation everywhere in the universe — the force of attraction which bodies and all particles of matter exert on each other. For the prese only the manifestation of this force by the earth and on relatively sm bodies on its surface or in the immediate vicinity of its surface will be co sidered. This local and limited portion of the vast universal force of a traction will be designated as the *force of gravity.*

This force cannot be eliminated from experimental work. It may locally neutralized or it may be kept at a constant value, as in motion o horizontal plane. We may well imagine what disastrous events would e sue on this rapidly rotating planet were this force suddenly to cease ope ting. However, there is no possibility of such an event taking place. may be sure that the forces of nature will continue to operate in accorda with natural law. Nor is it likely that man will ever be able to control t large-scale force. Locally and to a limited extent he has learned to ov come the force of gravity through the use of the airplane, the dirigible, a the elevator, or even when walking up a stair or a hill. But complete co trol would require complete understanding, and the fact of the matter that no one today knows why or how this force operates.

On the other hand, many things are known about the motions impart to bodies by this force. Since the force acts constantly, it must impart acceleration to freely falling bodies. The velocities attained and t distances such bodies fall may be calculated by use of the equations veloped in the preceding chapter. Two questions, however, must fi be answered. Does gravity act on all bodies, even on those of differe masses, with the same force? And what is the value of the accelerati or accelerations imparted to these bodies?

THE FORCE OF GRAVITY

ght and Heavy Bodies

According to the views advanced by Aristotle and generally accepted un- the time of Galileo, the velocity with which a body fell depended upon s nature and its mass. Accordingly, it was held that a five-pound mass ll five times as rapidly as a one-pound mass. No doubt the Aristotelians ere influenced by their observations of the rates of fall of bodies like leaves feathers in contrast to those of more compact materials like stone or etals. Galileo questioned these conclusions and by 1590 had completed och-making experimental studies. He actually tried dropping metal lls of different masses from heights to see what would happen. When veral balls of different masses were dropped simultaneously they fell the same rate and struck the ground at the same time. These experi- ents were carried out from the heights of the leaning tower in Pisa, alileo's native city, where at the age of twenty-five he was made lecturer the university. But the results did not convince the Aristotelians. This was not, as many have assumed, the inauguration of experimental ience. Scientists have always observed and experimented. Rather it as the beginning of that strict combination of scientific experiment and asoning upon which modern science is built. Galileo made observations, formulated an hypothesis, and he then planned and carried out a de- sive experiment to test his hypothesis. Moreover, he challenged the es- blished authority of his day and was one of the greatest of the leaders in e intellectual movement which finally freed science from the fetters of the st.

avity and Weight

The experiment described in the preceding section may be supplemented similar experiments. Even a feather, whose downward motion is re- rded by the resistance of air, falls at the same rate as a piece of lead a vacuum. It is therefore concluded from experiment that at any ven place on the earth's surface falling bodies have the same acceleration espective of their masses. If a five-pound mass is given the same ac- leration by gravity as a one-pound mass, then the force acting on the avier body must be five times as great as that acting on the lighter one. o put it mathematically, if two bodies of masses, M and m, are each al- wed to fall freely with acceleration, a, the forces acting on the two bodies e F and f.

$$F = Ma \text{ and } f = ma$$

ıce a is common to both equations,

$$a = \frac{F}{M} = \frac{f}{m} \text{ or } \frac{F}{f} = \frac{M}{m}$$

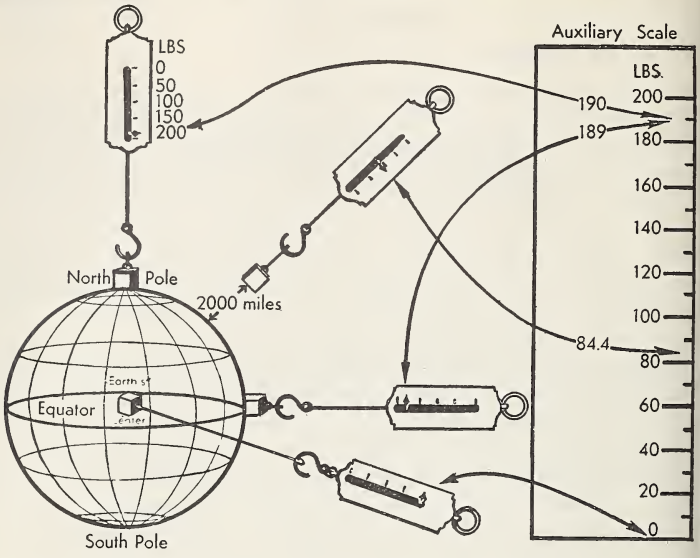


FIGURE 156. WEIGHT VARIES WITH DISTANCE FROM THE EARTH'S CENTE

The weight of a body is the force of gravity with which the earth attracts it. The force gravity, and consequently the weight of any object, is greater at the poles than at the equa less at a distance from the earth's surface, and zero at the earth's center.

which means that the force of attraction exerted by the earth on a body any given place is proportional to the mass of that body. This force commonly called the *weight* of the body. Since the earth is slightly fl tened at the poles, the weight of a body is a little greater there, where it nearer to the center of gravity of the planet, than at the equator. T actual difference is so very slight that for practical and commercial c siderations it may be ignored. If the body were projected out into spac few thousand miles, the weight would be considerably less; if it could moved toward the interior of the earth, the weight would also become le and at the center of gravity of the earth it would be attracted equally in directions, and the weight would be zero. Throughout all these hypothe cal changes in position the mass of the body remains constant. Weigh therefore a variable quantity, subject to variations in the force of grav at different distances from the earth, and is proportional to the mass of body. If one body has twice the mass of another body, it will also h twice the weight of the lighter body regardless of where they are weigh provided they are weighed at the same place. The spring scale indica the pull of gravity, or weight, of a body.

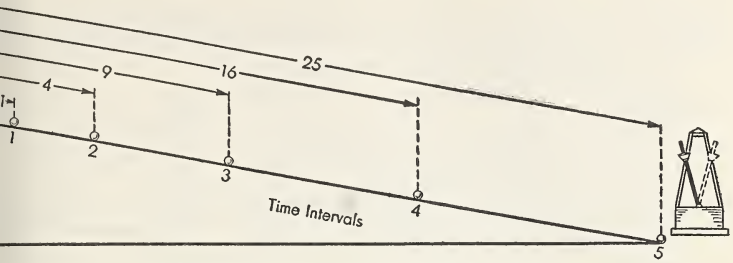


FIGURE 157. EXPERIMENT WITH ACCELERATED MOTION DUE TO GRAVITY
Ball rolls down smooth incline with uniform acceleration. Distance varies with the square *of the* time.

xperiments with Gravity

It has already been shown that a small sphere placed on a smooth hori- ontal surface remains at rest. Gravity acts upon it and tends to pull it ertically downward, but the surface prevents such motion. If a push or slight blow puts this ball in motion, it continues to move; if a force acts ntinuously on it, it is uniformly accelerated. Thus, if the surface is lted slightly, the force of gravity becomes effective and the ball rolls wn the incline with uniformly accelerated motion. If one end of the ane is elevated still more the acceleration increases; and, if it is finally evated 90°, the body falls freely.

It is with such a device that Galileo experimented with accelerated mo- on, for he found that freely falling bodies moved too rapidly to permit ccurate time measurements with the apparatus at his disposal. Such xperiments show that bodies moving under the constant force of gravity, o so in accordance with the equations already derived. By use of the etronome, a timing device which ticks off equal intervals of time (see igure 157), it may be shown that the distance varies with the square of e time. The velocity attained is proportional to the time.

ie Acceleration of Gravity

With modern apparatus the distance a freely falling body moves in ccessive units of time may be recorded electrically, and from this in- rmation the value of g, the acceleration of gravity, may be calculated. is approximately 32 feet per second per second, or 980 centimeters per cond per second, and, as the variation over the surface of the earth is ght, these values are used in illustrative calculations. The values of g, wever, have been accurately determined and are still being determined various points on the earth. At the poles g has its maximum value, and s value decreases to a minimum at the equator, where the radius of the rth is greatest. Accurate values for Washington, D.C., are 32.156 feet

per second per second, or 980.116 centimeters per second per second. Wit these values established, calculations for falling bodies may be readily made

EXAMPLE: A brick falls from the top of a high building and reaches the ground in five seconds.

1. *With what velocity does it strike the ground?* The equation $v = at$ is used, and, since we have a special value for acceleration, which is g, the equation becomes $v = gt = 32$ ft/(sec)$^2 \times 5$ sec $= 160$ feet per second, which is the final velocity.

2. *How high is the building?* In other words, how far does the brick fall in five seconds? Here the formula for distance may be used. $d = \frac{1}{2} at^2 = \frac{1}{2} gt^2 = \frac{1}{2}$ 32 ft/(sec)$^2 \times$ (5 sec)^2 $= 400$ feet, which is the height of the building. Another solution may be used: A falling body always falls sixteen feet during the first second (since the average velocity for the time interval is sixteen feet per second). According to the above equation the distance varies with the square of the time. Hence

$$d(\text{istance}) : 16 \text{ ft} = (5 \text{ sec})^2 : (1 \text{ sec})^2$$

and $$d = \frac{16 \text{ ft} \times (5 \text{ sec})^2}{1 \text{ (sec)}^2} = 400 \text{ ft}$$

3. *How far has the brick fallen at the end of each of the five seconds?* Since for all cases,

$$d = \tfrac{1}{2}\ 32 \text{ ft/sec}^2\ t^2 = \frac{16\ ft\ t^2}{\text{sec}^2}$$

At end of first second: $d = 16 \times 1^2 = 16$ ft
At end of second second: $d = 16 \times 2^2 = 64$ ft
At end of third second: $d = 16 \times 3^2 = 144$ ft
At end of fourth second: $d = 16 \times 4^2 = 256$ ft
At end of fifth second: $d = 16 \times 5^2 = 400$ ft

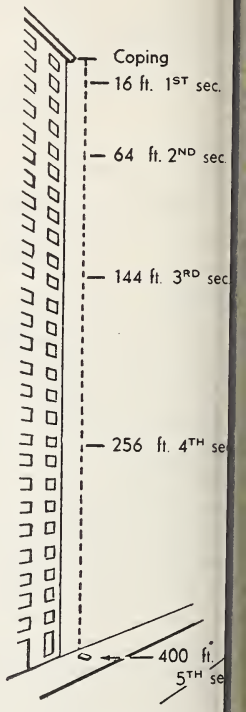


FIGURE 158
THE DISTANCE THROU WHICH A BODY FALLS PROPORTIONAL TO T SQUARE OF THE TIME
The above diagram represe the fall of a brick from top of a skyscraper.

Thus, falling bodies under the influence of only one force, that of gravity, move vertically with uniform acceleration. Let us now consider cases where two forces act simultaneously on a body.

PROJECTILES

Baseballs and Bullets

We shall consider first bodies which are given an initial horizontal locity and which, according to the Law of Inertia, tend to continue th uniform straight-line motion. As soon as such an object, which may

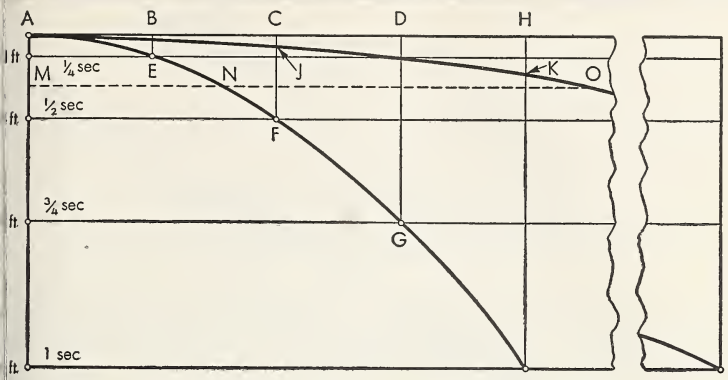


FIGURE 159. INFLUENCE OF GRAVITY ON TRAJECTORIES
Objects dropped and projected horizontally at the same time strike the ground simultaneously.

rown baseball or a bullet fired from a rifle, leaves the hand or the muz- of the gun, it becomes also a freely falling body subject to the acceler- ng influence of the force of gravity. The actual resultant motion of body is a curved path, but both of the component motions take place in ct. Such motion had not been correctly analyzed by scientists until lileo and others formulated the first law of motion (Law of Inertia) and rified the laws of falling bodies. The use of gunpowder initiated also ractical demand for such understanding of the law as applied to the hs of cannon balls.

n the drawing (Figure 159) are represented three objects. The first y be either a baseball or a bullet which is dropped from point A. The ond is a baseball thrown horizontally, and the third a bullet fired from un the barrel of which is perfectly horizontal. All three are projected m point A, which for convenience is 16 feet from the ground. Object nber one has no horizontal velocity and falls directly downward with an eleration g. The thrown baseball, although moving in a curved path, s two component motions — a horizontal uniform motion and a vertical formly accelerated motion, both taking place simultaneously. By the e it moves through the horizontal distance AB it also moves through vertical distance BE. In equal time intervals, it moves successively r equal distances BC and CD and simultaneously through vertical dis- ces which are not equal, to points F and G, respectively. The hori- tal distance from A at any moment may be calculated by the equation uniform motion, $d = vt$, while the vertical distance from A at the same ment may be calculated by use of the equation for falling bodies, $= \frac{1}{2} gt^2$. The same conclusions hold for the bullet despite its greater

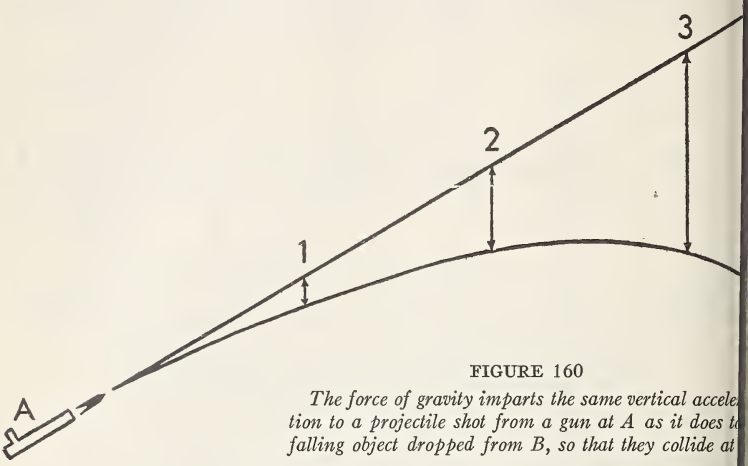


FIGURE 160

The force of gravity imparts the same vertical accele tion to a projectile shot from a gun at A as it does t falling object dropped from B, so that they collide at

velocity. As it moves successively over equal horizontal distances *A* and *CH*, it falls vertically through distances *CJ* and *HK* minus *CJ* respe tively. Still more astonishing is the fact that all three objects reach t ground at the same time. At any moment during their flight they are three vertically equidistant from *A* or from the ground as indicated by t line *MNO*. Thus, *when a body is under the influence of two or more motio the particular final effect of each motion is realized independently of the othe*

A Slow-Moving Projectile

The law of independence of motions is admirably demonstrated by laboratory experiment with a slow-moving projectile. The blow-gun which projects a dart, is aimed at an object *B*, which is released at the stant the dart leaves the muzzle of the gun. Regardless of the speed the dart or the angle at which the gun is placed, the two collide in air some point *C*. Here again, uniform linear velocity is imparted to the p jectile in the direction of *B*. If gravity did not exist, the projectile wo move in a straight path and strike *B* at *B*. But the force of gravity a independently upon the projectile, imparting to it the usual vertical celeration, just as it acts upon *B*. Hence the projectile follows a curv path, traversing in successive seconds (if the flight be sufficiently p longed) the total distance of 16 ft, 64 ft, 144 ft, etc., from points 1, 2, etc., in accordance with the equation $d = \frac{1}{2} gt^2$.

The wind also tends to add another velocity to a moving body. airplane moving with velocity *V* (Figure 161) may be deflected from

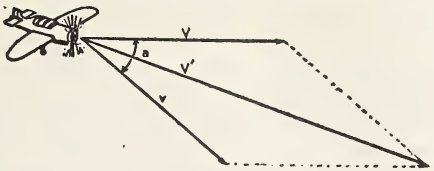


FIGURE 161. COMPOSITION OF VELOCITIES

Velocity V imparted to an airplane by its engine combines with the velocity v imparted by the wind to give it velocity V'.

ath by a cross wind of velocity v. The actual resultant motion of the lane may be calculated by trigonometric methods if V, v, and the angle a re known. Or it may be determined graphically by completion of the arallelogram and construction of the diagonal V' which represents vec- orially the quantity sought.

he Range of Projectiles

The *range* or *horizontal distance* through which the projectile travels de- ends upon two factors: the horizontal velocity and the time of flight. or bodies that are projected horizontally, the time of flight is limited to ie time required for the object to fall vertically to the ground. (Refer o Figure 159.) If the ball or bullet is started on its flight at a distance of ve feet from the ground, it can continue only for a little more than one- alf of a second (0.557 sec). If the ball is thrown with a velocity of fifty et per second, it strikes the ground 27.85 feet from the thrower; if the uzzle velocity of the bullet is two thousand feet per second its range is 114 feet. To increase the range for a given initial velocity, one must ngthen the time of flight. This may be done by elevation of the thrower r marksman, while still restricting him to horizontal projection. But aseball players and soldiers do not ordinarily find it feasible to climb to eights in order to extend their range. Rather they elevate their throw or un in a direction above the horizontal (Figure 162).

If the gun were pointed straight up in the air (elevation of 90°) the time

FIGURE 162

If a projectile is shot from a gun at an elevation of 45°, the horizontal and the vertical components of the muzzle velocity are equal. Air resistance is neglected.

of flight would be at its maximum value, but the horizontal component o its velocity would be zero. On the other hand, at 0° elevation (horizontal) the time of flight is at its minimum value. It can be shown mathematically that the maximum range is obtained when the angle of elevation is 45° (Figure 162.) At this angle the vertical and horizontal components of the muzzle velocity are equal. For slow-moving objects, like shotput or discus, the angle of 45° does give the greatest distance. But for high velocity projectiles fired from guns the air resistance becomes a factor and the elevation must be increased to give the maximum range.

Other factors which must be considered in making calculations for long range projectiles are wind velocity, rotation of the earth, and the curvature of the earth. The cannon which fired upon Paris during the first World War was elevated 55.5°; the shell reached a maximum height of twenty four miles and had a range of seventy-six miles. At such a great height the air resistance was considerably less. But, even so, it reduced both height and range to less than one half of their theoretical values — that is, the values obtained by calculations in which the air resistance is neglected.

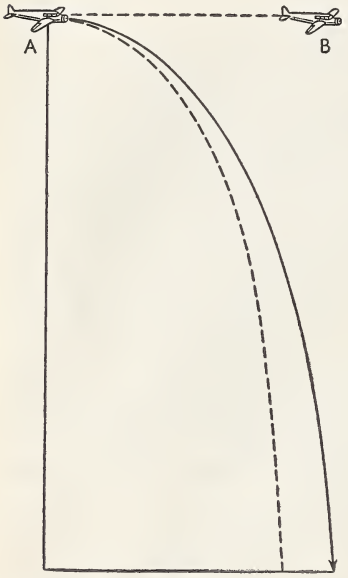


FIGURE 163. TRAJECTORY OF BOMB

Solid line shows path in a vacuum, dotted line the actual path in air. If bomb is released when plane is at A, it would strike ground just below plane at B if latter continued to move uniformly in horizontal direction and if there were no air resistance.

Bombs

The principle of independence of motions is applicable to bombs dropped from moving airplanes. The forward or horizontal velocity of the bomb is that of the bomber, which is flying horizontally. At the same time the bomb is given an acceleration vertically downward by the force of gravity. As is true of all other objects projected into the air, the path followed is theoretically a curve known as a parabola. But this is true only if the air resistance is negligible. Experiments show that the vertical velocity of the bomb increases uniformly thirty-two feet per second during the first five seconds of fall and that the horizontal velocity remains constant during the first few seconds. After these intervals both the acceleration downward and the forward velocity decrease slowly

due to the resistance of the air, which increases with the square of the velocity of the projectile.

As with other projectiles there are a number of factors which determine the path (Figure 163). In addition to air resistance, the ground velocity of the plane (the horizontal velocity relative to the ground), the velocity and direction of the wind, and the velocity and direction of the target must be taken into account in sighting the bomb.

AIR RESISTANCE

Terminal Velocity

It has been shown in the preceding paragraphs that air, like other materials, has inertia and resists being pushed aside by objects moving through it. This resistance is not great for bodies moving with relatively low velocities, but for a given body it increases approximately in direct proportion to the square of the velocity. Hence for high-speed bodies like projectiles (see preceding paragraph), airplanes, and even automobiles, it is of considerable importance. A train may accelerate and finally attain such speed that the air resistance and other friction just equal the propelling force. From then on it moves with a uniform velocity which is called the *terminal velocity*. Automobiles and all moving objects have a terminal velocity, which may or may not be attained. Attempting to run with an open umbrella, one soon reaches this limiting velocity. These bodies just mentioned all encounter friction with the earth, which, of course, tends to lower the terminal velocity.

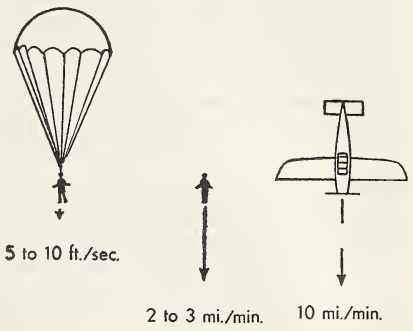


FIGURE 164. TERMINAL VELOCITIES

Man with opened parachute, man alone, and nosediving airplane

Freely falling bodies may attain higher velocities, for they have only the friction of the air to oppose the force of gravity. The parachutist who fails to pull the cord does not fall with a continued acceleration of thirty-two feet per second per second, but, as his velocity becomes greater, the acceleration diminishes, and finally, when the terminal value of his velocity is reached, the acceleration becomes zero. He does not stop under such circumstances but continues to fall with a terminal velocity of approximately 150 to 175 miles per hour. If the parachute is now opened, terminal velocity is diminished to the extent that a safe landing may be made.

The shape of a moving object, therefore, is another factor that determines the amount of air resistance and will be discussed in the next section.

Modern high-speed airplanes are sometimes tested for terminal velocity. With the aid of both the force of gravity and that of the engine, diving speeds of over ten miles per minute (almost as great as the velocity of sound) have been attained. With some planes, the design has so reduced the air resistance that the terminal velocity has never been attained.

Streamlining

Since the air friction becomes greater at high speeds, special attention must be paid to the shape and design of fast-moving objects. While the term *streamlining* is somewhat new, the principles involved are very old. In nature we find streamlining wherever we find a great fluid resistance. A falling drop of water assumes such shape that the air offers a minimum of resistance. Fishes are streamlined, for they move through a fluid which offers great resistance even at low speed. A bird that moves through the air with great speed also has a shape that meets with the least resistance. Man copied nature, and his first use of this principle was in boat design. Boats, like fish, must move through a much more dense and inert fluid than air, and streamlining is an absolute necessity. More recently man has devised vehicles that move rapidly through the air. The airplane, the first of these to be streamlined, resembles a bird very much in both body and wing design.

Since 1920, automobiles have utilized streamlining — at first in their carburetors and manifolds, where the rush of air and gases takes place at very great speed. In body design there is the appearance of streamlining even to the door handles. The upper part of the body with the sloping windshield and the long tapering rear does offer somewhat less resistance to the air, especially at speeds of fifty miles per hour or more. The under part of the automobile is not streamlined at all. Recently passenger trains which ordinarily run at sustained high speeds have adopted such design with excellent results.

The resistance offered to the motion of a body passing through a fluid is to a large extent due to eddy currents set up at the rear. This turbulence in the wake of the body is a region of low pressure and also is formed at the expense of the energy of the body. One may observe eddy currents in the water at the rear of a rowboat, or in the air as indicated by paper and dust following the rear of a moving train.

True streamlining design permits passage through air or water with the minimum of disturbance. The shape of the rear of the body is of greater importance than a sharply pointed front.

SUMMARY

1. The force of the earth's attraction, which is known as *gravity*, imparts to freely falling bodies an acceleration of approximately 32 ft/sec^2 or 980 cm/sec^2.
2. The force exerted by gravity upon different bodies is in direct proportion to their respective masses.
3. *Weight* is the force with which the earth attracts a body. Weight varies according to the distance of a body from the center of gravity of the earth. The weights of objects at any given place are proportional to their masses.
4. Freely falling bodies move in accordance with the equations for uniformly accelerated motion.
5. A moving body influenced by two or more directional forces responds to each independently.
6. The principle of independence of motions applies to projectiles, but air resistance is an important factor.
7. Air resistance, which increases approximately with the square of the velocity of a body, may equalize the force of gravity and bring the body to a terminal velocity.
8. Man has copied nature in streamline design for the purpose of lessening fluid resistance.

STUDY EXERCISES

1. Bodies A and B, having masses of one pound and ten pounds respectively, are dropped simultaneously from the top of a high building. Compare the two with respect to the points enumerated below, and where there is a difference indicate which is greater and, if possible, by how much.
   ..... Accelerations imparted.
   ..... Velocities attained at the end of t seconds.
   ..... Momenta at time of striking ground.
   ..... Weight of A on ground compared with that of B.
   ..... Weight of A on top of building compared with that of A on the ground.
   ..... Force which gravity exerts.
2. From the equation $F = ma$ show that the force of attraction which the earth exerts on a body at a given place is proportional to the mass of that body.
3. In the table below are experimental data obtained by observation of a ball rolling down an inclined plane. First, from the distance the ball moved dur-

Time (t) seconds	Total distance (feet)	t^2	Velocity at end of each second	Change in velocity each second
0	0			
1	2			
2	8			
3	18			
4				
5				

ing the first second, determine its acceleration and answer the question below, then fill in all the blank spaces in the table, including those in the column for distance.

(*a*) What is the acceleration?

(*b*) How may it be increased?

(*c*) What is the limit of the acceleration which the ball on the inclined plan may attain?

4. What velocity is attained by a body falling for eight seconds in a vacuum? What distance does it fall in that time?

5. Decide which of these statements are true, which false:

..... (*a*) Should gravitational attraction cease, a ball thrown into the air would continue upward at a uniform velocity.

..... (*b*) A ball dropped from the mast of a ship moving with uniform velocity strikes the deck directly below the point from which it is released.

..... (*c*) The air resistance is the same for a thrown ball as for a high speed projectile the same size.

..... (*d*) A hunter points his rifle directly at a monkey sitting on a limb one thousand feet away; when the monkey sees the flash of smoke he drops, thereby saving his life.

..... (*e*) Two bombers flying at the same height but at different horizontal speeds each releases a bomb simultaneously. The bombs strike the ground at the same time.

6. *Given*: A body having a mass of ten pounds falls freely from rest with a uniformly accelerated motion. The acceleration is thirty-two feet per second per second.

Select the answer that completes each statement correctly:

..... (1) In five seconds it will fall a total distance of (*a*) 80 ft; (*b*) 160 ft; (*c*) 320 ft; (*d*) 400 ft; (*e*) 640 ft.

..... (2) Its velocity at the end of ten seconds will be (*a*) 160 ft per sec; (*b*) 240 ft per sec; (*c*) 320 ft per sec; (*d*) 480 ft per sec; (*e*) 640 ft per sec.

..... (3) If it falls a total distance of 1024 feet, its velocity at the end of the fall will be (*a*) 256 ft per sec; (*b*) 640 ft per sec; (*c*) 160 ft per sec; (*d*) 80 ft per sec.

..... (4) The time required to fall 576 feet will be (*a*) 3 sec; (*b*) 4 sec; (*c*) 5 sec; (*d*) 6 sec; (*e*) 7 sec; (*f*) 8 sec.

..... (5) The force acting on the body is (*a*) 320 dynes; (*b*) 320 poundals; (*c*) 980 dynes; (*d*) 980 poundals; (*e*) 32 poundals.

7. Select the correct answer in each parenthesis:

(*a*) A bomber flying at an altitude of 6400 feet releases a bomb. It strikes the ground in (5, 10, 20, 30, 40) seconds.

(*b*) A marksman fires a rifle at a target so placed that it takes one second for the bullet to reach the target after leaving the muzzle of the gun. To hit the bull's-eye the bullet must start toward a point (4, 8, 16, 24, 32, 64) feet above the target.

(*c*) A bomber flies at an altitude such that a bomb requires ten seconds to strike the earth. If his speed is 440 feet per second he must drop his bombs (2200, 3300, 4400, 5500, 6600) feet before he reaches a point directly above his target.

8. Write a concise explanation of each of the following phenomena, utilizing if necessary a knowledge of the laws of motion, the rotation of the earth (Chapter 4), and the principle of independence of motions. Make a drawing for each case.
   (*a*) A bullet which is fired vertically upward will return exactly to the point from which it was fired, provided no air currents interfere.
   (*b*) A falling body reaches its terminal velocity when the air resistance just equals the pull of the earth. As there is no net force actually on it, why does it not slow up considerably or even stop?
   (*c*) For automobiles, streamlining is primarily a matter of appearance, while in airplanes it is a necessity.
9. An airplane is headed directly eastward at a velocity of two hundred miles per hour. A cross wind is blowing to the south at a velocity of sixty miles per hour. Make a scale drawing to show the actual path of the plane and calculate its velocity along that path.
10. A bomber flying at an altitude of sixty-four hundred feet and with a velocity of two hundred and fifty miles per hour, releases a bomb. How long does it take the bomb to reach the ground? How far from a point on the ground directly below the plane at the time of release does it hit? (Neglect air friction.) Make a drawing.
11. A bullet with a speed of two thousand feet per second is fired in a horizontal direction four feet from the ground. What is its range? (Neglect air friction.)
12. Write a short discussion to show why Galileo is regarded as the father of modern experimental science, although scientific observation and experiment were utilized before his time.

FOR FURTHER READING

1. Lemon, H. B., *From Galileo to the Nuclear Age.*
   Chapters 3, 4, and 6 are excellent chapters on falling bodies, terminal velocity, and the paths of projectiles. Illustrations are amusing yet to the point.
2. Mott-Smith, M., *This Mechanical World.*
   Chapters VI, VIII, IX, and XIV discuss Galileo's work on falling bodies and the principle of independence of motions, mass, and weight. "As exciting as fiction."
3. Stephenson, R. J., *Exploring in Physics.*
   Chapter 3 supplies more problems on momentum and projectiles.
4. Taylor, L. W., *Physics, the Pioneer Science.*
   Chapters 3 and 16 give a more advanced treatment of falling bodies, projectiles, impact, and momentum.
5. Freeman, I. M., *Invitation to Experiment.* New York: E. P. Dutton & Company, Inc., 1940.
   Basic scientific principles in all branches of physics are explained in simple language and illustrated by experiments which may be performed at home with commonplace things.

13

"And Yet It Does Move"

IN OUR FIRST LOOK at the world (Chapter 4) the general arrangement of th solar system, as accepted today, was presented. The sun is at the cente and the earth and other planets rotate on their axes and revolve aroun this great body. It is easy for us today to accept such a cosmograph (*kosmos*, world, + *graphein*, to write), supported by data and evidenc which represent the accumulated discoveries of mankind in this fiel This picture of the solar system, however, was not so easily formulated an established; it is the product of a long, difficult, and at times painful proce of development.

Much of the observational data was not accurate because of the shor comings of the instruments of the time. There were hypotheses base upon false principles of mechanics, and there was one very long period stagnation. Some of the crucial evidence was not found until after th recent development of powerful astronomical telescopes. Yet there we dramatic events and many great and inspiring achievements.

With our knowledge of the elementary principles of motion and for as expressed in Newton's laws (Chapter 11), and with a working knowledg of the scientific method, we may now trace the evolution of our prese ideas of the solar system.

EARLY ASTRONOMY

When man first paused to look at the sky, to wonder and to tell what h saw, astronomy was born. The process of birth, however, was a long on for man's early struggle with nature so preoccupied him that his body an mind were not free for prolonged observation and thought. No doub the sun, which gave him light and heat, dominated his daily life even mo than it dominates our own. From the daily apparent motion of this bod he probably developed a sense of time and of direction. The period cycle of changes (phases) taking place in the illuminated face of the moo and ultimately the cycle of the seasons gave him a means of measurin longer units of time. While traveling over the country, he learned to d

pend upon the more fixed bodies in the sky, the stars, as guides. Strange events were sometimes seen. The moon and, less frequently, the sun were in eclipse; comets trailed through space, or meteors rushed across the sky. These awe-inspiring events were thought by some tribes to be physical manifestations of the gods; and so the sun, the seasons, and other astronomical bodies and events came to be worshiped.

The Babylonians and Early Egyptians

Leaving the long period of prehistoric mankind, about which we know so little, we come to the time of the earliest known written records. Beginning about 5000 B.C., records of the Babylonians and the early Egyptians indicate that astronomy was widely cultivated by these peoples. The eclipses of the moon and sun, the appearances of comets, and the movements of planets were recorded over long periods of time. Such data permitted the computation of the length of the year and the prediction of eclipses and planetary motions with surprising accuracy. Use was also made of these data in the alignment and orientation of some of the temples and of the Egyptian pyramids. Their astronomy was observational and mathematical, but limited by the primitive instruments of the period. No scientific hypothesis on the scheme of the solar system was recorded. On the contrary, man's factual knowledge was still allied with superstition and the belief that his fate was somehow linked with the movements of the sun, the moon, and the planets. The scientific method was yet to be fully developed. And it is still far from being universally applied. That such beliefs are current among a surprising number of present-day people is attested by the fact that no fewer than a dozen professional astrologers are listed in the classified telephone directory of one of our large cities.

The Greeks

It is indeed fortunate that the data compiled by the Babylonians and the Egyptians were inherited by the Greeks. These vigorous and intellectually daring people were free from dogma and superstition and were thus able to indulge in speculative thought and inquiry. During the long and fruitful period beginning with Thales of Miletus (seventh and sixth centuries B.C.) and ending with Ptolemy (A.D. 100–170), much progress was made in astronomy. The scientific method was gradually formulated, better instruments were constructed, and great advances in mathematics, the tool of the astronomer, were made. The Greeks firmly believed that the universe was orderly and that its workings could be reduced to general principles and theories in harmony with the great body of facts. They therefore paid considerable attention to the problem of accounting for the motions of the heavenly bodies and to the place of the earth in this scheme.

Thales, utilizing the data of his predecessors, successfully explained the phases of the moon and predicted a number of eclipses. To him and his

contemporaries the earth was a disk floating in a sea of water. Pythagoras (550 B.C.) was probably the first to say that the earth is a sphere, at rest but in the center of a rotating universe. Eudoxus (407–355 B.C.) proposed the first consistent mathematical theory, with the earth at the center of the universe. Although the geocentric (earth-at-center) theories were widely accepted, yet, as always, there were persons who challenged the accepted and orthodox views. Aristarchus of Samos (280 B.C.), a follower of Pythagoras, proposed a heliocentric system, with the sun in the center of the universe and the earth rotating on its axis and also revolving around the sun. Though a century later the heliocentric theory was taught in Babylonia, it did not gain wide acceptance. Hipparchus (140 B.C.), perhaps the greatest of ancient astronomers, realized that the observed facts and existing theories were both inadequate to explain the motions of the sun, stars, and planets. He made a star catalogue which ultimately included about one thousand stars and remained the dictionary of the heavens for sixteen hundred years. He invented the principles of trigonometry and made prolonged and systematic series of observations. Unfortunately, he chose the geocentric system and devised a combination of uniform circular motion which would account for the motions of heavenly bodies in accordance with the then known observations.

Three hundred years later, Ptolemy, the last of the ancient astronomers, prepared a compendium of the known astronomical science. In this work, which he called the *Mathematical System of Astronomy* and which was later known from the Arabic translation as the *Almagest*, he supported and made little change in the geocentric theory of Hipparchus.

THE GEOCENTRIC, OR PTOLEMAIC, SYSTEM

Two facts had great influence in the formulation, the acceptance, and the survival of this hypothesis without changes for over thirteen hundred years. First, the most obvious and natural explanation for the apparent daily motion of the sun and stars from east to west was to conclude that these bodies revolved around the earth. Second, it was flattering to human vanity to regard the earth, the home of man, as the center of the universe. It is this fact, particularly, which accounted for the dominance of this hypothesis during the Middle Ages and until rather recent times. Any attempt to dethrone man from his central position by mere facts met with bitter opposition.

The geocentric system was in accord with the known facts of the time as incorporated in the extensive data compiled by Ptolemy. The periods of revolution of the planets, of the sun, and of the moon, as well as their paths among the stars, were all satisfactorily explained. The irregular movements of the planets gave some difficulty. Viewed from the earth, Mars, for example, moves forward in its direct eastward motion, then

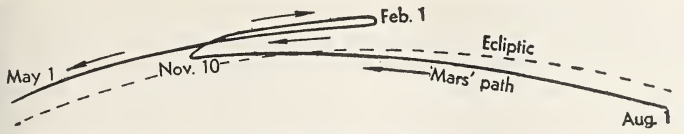


FIGURE 165. THE RETROGRADE MOTION OF MARS AS OBSERVED FROM THE EARTH

ows down, and for a shorter time moves westward with retrograde otion; then it resumes the direct motion as shown in Figure 165. This trogression of the planets was accounted for by assuming that each planet volved in a small circle, or *epicycle*, the center of which in turn moved in e planetary orbit or deferent around the earth. The entire system is presented in Figure 166. The sun lay between Venus and Mars, so that Mercury and Venus were between the earth and the sun, and the center of heir epicycles was always aligned with the earth and the sun. The planets nd the sun thus moved eastward around the earth, the sun requiring one ear for its complete revolution. Beyond the orbit of Saturn was the here of fixed stars, which did not move eastward with the planets and n, while beyond the stars was the *Primum Mobile*, which daily rotated e entire system westward around the earth.

The enormous amount of mathematical computation and the skill with hich it was made in accounting for the motions and positions of the lanets at any time must command our respect. It is probably true that

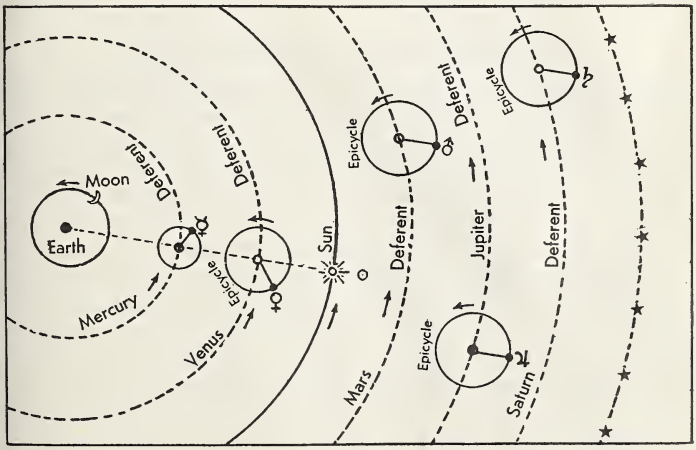


FIGURE 166
THE SOLAR SYSTEM ACCORDING TO THE PTOLEMAIC HYPOTHESIS

the authors of this system placed greater emphasis upon it as a mathe matical basis for such computation than as a picture descriptive of th universe. As scientists they no doubt expected criticism, but they ha worked very carefully and had not found anything in the data then extan which was in serious conflict with their hypothesis. With the naked ey they could not observe any parallactic displacement of the nearer star relative to the more distant stars — a phenomenon which indicates a orbital motion of the earth (Chapter 4). Nor could they observe an phase changes on the surfaces of Venus and Mercury. In fact, they kne nothing of these phenomena nor any others which might support a helio centric hypothesis. On the other hand, they presented some argument against a moving earth which today seem absurd. If the earth move they reasoned, why were not birds in flight and objects thrown in the a left behind?

Unfortunately, long after the decline of Greek science the Ptolema system was universally accepted without challenge, and was personalize and handled in much the same way as some of the totalitarian ideologi are today. An hypothesis or even a theory should always be open to ne facts and to revision or abandonment. Science in this way progresse Facts are explained by an hypothesis which in turn stimulates the searc for more facts. When the latter step is prevented or discouraged, scien and thought stagnate, and such was the fate of science for nearly fourte hundred years during the Middle Ages. The reawakening came slowl and with it a new cosmography which gradually won acceptance an which brought about a spiritual revolution and a rebirth of science.

THE HELIOCENTRIC, OR COPERNICAN SYSTEM

The real scientific knowledge of the Greeks had not all been lost. In th Christian Byzantine Empire (A.D. 300–1204), Greek culture and scien were preserved, but no notable advances were made. Farther east, th Hindus and Arabs maintained some threads of authentic Greek cultu dating from the time of the conquests of Alexander, and the Hindus d veloped the so-called Arabic scheme of numbers. In Spain, the Aral Moors, who reached a high degree of enlightenment by the eleventh ce tury, showed independence in science and medicine and achieved gre skill in the arts. The spread of these cultures into the rest of Europe w greatly facilitated by the Crusades. The Renaissance was in preparatio

Beginning with the thirteenth century, a few independent thinkers Europe attempted to deliver the world from intellectual darkness. Rog Bacon (1214–1294), a man of broad interests, who carried out independe investigations in practically every field of science, including astronom placed great emphasis on observation and experiment. Leonardo Vinci (1452–1519), one of the most versatile geniuses of all time, in e

gineering, in the sciences, and especially in the arts, favored a heliocentric osmography. Far ahead of their times, neither exerted any appreciable mmediate influence on science.

Copernicus

Nicholas Copernicus (1473–1543), a Polish-German astronomer who ater became a canon of Frauenburg Cathedral, was the first to challenge he Ptolemaic system successfully. Copernicus examined the writings of ome of the early philosophers and rom them obtained the idea of a eliocentric system. Because he vas an excellent mathematician, e was able to make a thorough nalysis of Ptolemy's work. Aided y tables of planetary motions vhich he had carefully prepared, e formulated a new astronomical ystem which, although less appar- nt than the Ptolemaic scheme, was eometrically simpler and more rea- onable. He assumed that the sun, ot the earth, was the center of he system, and that the planets, ncluding the earth, revolved uni- ormly around it in circular orbits. he apparent retrograde motions of he planets can thus be easily ex- lained. The nearer a planet is to he sun, the faster it moves in its rbit, so that the earth overtakes nd passes the superior planets.

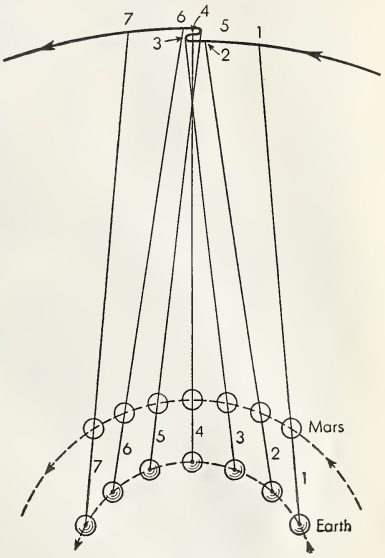


FIGURE 167

Observed from the earth against he background of stars which serve s a reference framework, Mars, or example, moves forward (1, 2, Figure 167), and when the earth over- akes it (3) appears to stand still, and then to move backward for a time fter the earth passes. The same effect is perceived when a fast train or utomobile passes a slower, provided the observer on the fast train can gnore the landscape and concentrate on the other train. Hence the picycles are not required by the Copernican system in order to explain his phenomenon.

But there were yet many small variations in the motions of the planets o be accounted for. As Copernicus insisted on circular orbits, he had to ssume a few small epicycles, and a different center for each planetary

FIGURE 168. NICHOLAS COPERNICUS
1473–1543
(From D. E. Smith's "Portraits of Eminent Mathematicians," published by Scripta Mathematica, New York City)

orbit to account for these irregular motions. The sun was therefore not quite at the center of any of these orbits. The Copernican system accounted for the known motions and facts, but such evidence was not conclusive, for the Ptolemaic system did likewise. There were yet two crucial points of evidence to be found. One was the parallactic displacement of the stars, which has already been mentioned (page 65) and which was not observed until recently (1830). Such displacement indicates motion of the earth. The other had to do with the phases of the inferior planets, Mercury and Venus. In the Ptolemaic system the centers of the epicycles of these two planets were permanently aligned between the earth and the sun to explain their back-and-forth motions relative to the sun. Hence only a small edge of each of these planets, illuminated by the sun, could be visible to observers. (Figure 169.) On the other hand, according to the Copernican scheme, these planets revolve in orbits between the sun and the earth's orbit. They should therefore show different phases, just as the moon does, for at times they may be on the opposite side of the sun from the earth and at other times between the sun and the earth. (Figure 170.) The issue was clear-cut, and Copernicus predicted such phases, although he had no means of observing them. Sixty-seven years later, Galileo, using his telescope, observed the phases of Venus.

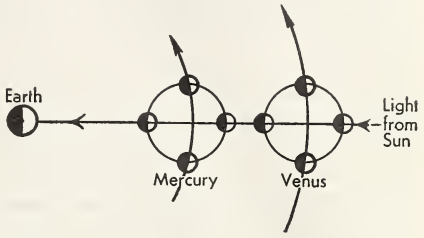


FIGURE 169

According to the Ptolemaic hypothesis only a small edge of Mercury or Venus is ever visible to the observer on the earth.

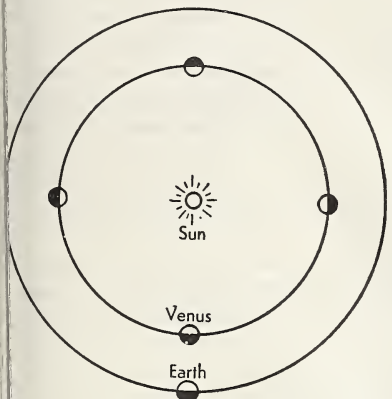


FIGURE 170

According to the Copernican scheme Mercury and Venus undergo phase changes as viewed from the earth.

Copernicus prepared his famous book, *De Revolutionibus Orbium Celestium*, but its publication was delayed until shortly before his death. His great hypothesis slowly won adherents, served as a great stimulus to scientists, and had far-reaching effects on the thoughts of man.

Galileo

Galileo, an Italian astronomer of whom we have heard much before, be came a warm supporter of the Copernican hypothesis. Hearing of th invention in 1608 of a telescope or "spyglass" by the Dutch optician, Han Lippershey, Galileo at once saw its great possibilities for astronomica observation. A year later he completed his own telescope, which con sisted of lenses placed at either end of an organ pipe and which had magnifying power of about three diameters.[1] Again Galileo was the lead ing actor in one of the great dramas of science. Turning his telescop toward the heavens, he saw things that were astonishing but indubitabl In due time he observed that Venus passes through phases just as the moo does, as predicted by Copernicus. His successive observations of sun spot convinced him of the rotation of that body. He observed many stars fo the first time, nebulae, the mountains on the moon, the small oscillation (librations) of that body, the rings of Saturn, and four satellites revolvin round Jupiter.[2]

In further support of the Copernican view, Galileo also cited even on the earth, such as tides and trade winds, which he explained as due the rotation of the earth. His principles of motion, particularly the Fir Law, explained why objects that are thrown into the air and birds in fligh are not left behind, but move along with the rotating earth. Galileo pr sented the entire matter in discussion form in his famous work, *Dialogu on the Two Chief Systems of the World, the Ptolemaic and the Copernica* which as a piece of scientific literature ranks with Copernicus' *Revolution* and Newton's *Principles*. Galileo's revolutionary ideas, which he so ab set forth, aroused considerable opposition on the part of the establishe authorities, and in the end he was forced to recant. After this humiliatin experience, the story goes, he muttered to himself with reference to th earth the words, "*And yet it does move!*"

With all this new proof there was still the dilemma of the irregularitie in the motions of the planets and the assumption of their uniform circul motion. More accurate observations and a more complete mathematic treatment were needed. Fortunately, about ten years before Galileo use his telescope, a great observer, Tycho Brahe, had completed extensive an accurate astronomical observations which he turned over to one of h younger co-workers, the great mathematical astronomer, Johann Kepl These men were destined to solve the problem of planetary motion and lay the foundation for Newton's great synthesis, the Law of Gravitatio

[1] Galileo later constructed a telescope which had a magnifying power of thirty diameter

[2] Seven additional satellites of Jupiter were discovered after the construction of more po erful telescopes.

ycho Brahe

Tycho Brahe (1546–1601), a Danish nobleman, was the greatest of all aked-eye astronomical observers. With a grant from the King of Denark he constructed the great observatory of Uraniborg (the Tower of eaven) on the island of Hveen. There he made a series of observations er a period of twenty-one years.

He developed instruments of size and accuracy never before known. eginning with such crude instruments as the astrolabe, then used by avigators, he soon saw the necessity for improvement. He accordingly d constructed a huge quadrant having a radius of about nineteen feet d a finely divided scale. He also had built a large theodolite with both rtical and horizontal scales. These instruments, however, were designed r naked-eye astronomy (for the telescope had not yet been introduced) d had to be carefully sighted by the alignment of small openings or ints in somewhat the same fashion as a gun is aimed.

Brahe searched in vain for some parallactic displacement of the stars d, unaware that the great stellar distances excluded observation of this enomena with his instruments, rejected the Copernican system and veloped one of his own. In the Tychonic system, as it was called, the ationary earth is at the center; the sun and moon revolve around the rth; the other planets revolve around the sun. This system won few herents, and Brahe is known primarily for his accurate and extensive servations of the positions of the planets. Before his death, Brahe oved to Prague to become director of the observatory and there conued his observations for a few more years.

pler

While a student, Johann Kepler (1571–1630), a German mathematician d astronomer, was converted to the Copernican doctrine. He became nvinced that the universe and, specifically, planetary motions were verned in accordance with exact principles, and he spent the greater rtion of his life in research on the problem. The publication of some of s early speculations brought him to the attention of Galileo, with whom later carried on a correspondence, and also brought him an invitation m Tycho Brahe to continue his researches at Prague. Here he was able test some of his hypotheses against the accurate data which Brahe had cumulated. He was so impressed with the accuracy of Brahe's instruents and observations that he discarded his own and other hypotheses hich were not in agreement with them. Upon Brahe's death, Kepler herited this vast store of accumulated observations. In accordance with previous agreement with Brahe, Kepler completed a series of observaons which were published as the *Rudolphine Tables* (after King Rudolph Bohemia, their sponsor).

Despite ill health and poverty, which at times forced him to teach a even to practice astrology, he kept persistently at work for more th twenty years on the problem of planetary motions. The data of Bra showed that the planets do not follow the paths prescribed by either t Ptolemaic or the Copernican systems. Each planet was shown to mo at a variable speed, which increases as the planet moves closer to t sun and decreases as the planet recedes from the sun. To account this motion he tried many different curves — circles with epicycles, ecc tric circles — each hypothesis involving an enormous amount of calcu tion. Finally, the ellipse (Chapter 4) occurred to him as a possibility and it worked. He found that if the sun were placed at one of the fo then there was a close agreement between theory and Brahe's obser tions.

Kepler's Laws. As a result of his long analysis he was able to sum planetary motions in three very important laws, the first two of wh were announced in 1609, the third in 1619.

(1) Each planet moves in an *elliptical orbit* about the sun, with the s at one focus of the ellipse.

(2) A line joining the center of each planet to the center of the s sweeps over *equal areas* in *equal intervals of time* (Law of Areas).

(3) The squares of the periods of revolution of any two planets proportional to the cubes of their mean distances from the sun (Harmo Law).

The path of the earth and, in fact, the paths of all the planets exc Mercury and Pluto are ellipses of low but different eccentricities. That they are almost circular. If drawn to scale, the orbit of the earth, example, appears to be like that shown in Figure 171. When the ea

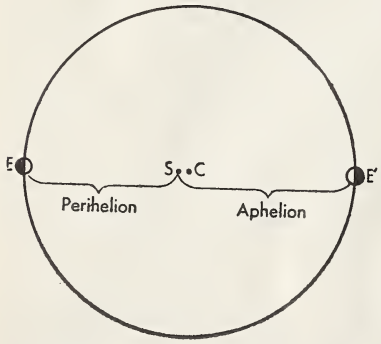


FIGURE 171. THE ECCENTRICITY OF THE EARTH'S ORBIT

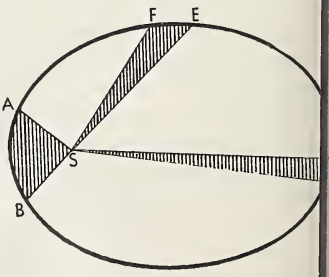


FIGURE 172

The orbital speed of a planet varies in accordance with the law of areas

nearest to the sun, or at perihelion, on January 1, it is some 3 per cent
ıbout three million miles) nearer than when it is farthest away, at aphe-
on, on July 1. That is, the distance from the sun to the center of the
lipse is approximately 1.5 million miles, while the distance from the
:nter to aphelion or perihelion is roughly ninety-three million miles.
ence, the eccentricity of the earth's orbit = 1.5/93 = 0.016.

The Law of Areas expresses clearly without the need of mathematical
quations the relationship between proximity to the sun and the orbital
)eed of the planet. At perihelion, for example, the earth is moving with
s greatest and at aphelion with its least speed. In Figure 172 the eccen-
icity of the orbit is exaggerated. The planet moves from A to B in the
me time as that required for it to move from E to F or from C to D.
ence, area BAS = area CDS = area EFS, and so on.

The Harmonic Law (Kepler's Third Law) is expressed by the equation

$$\frac{[T(\text{ime})]^2}{[t(\text{ime})]^2} = \frac{[D(\text{istance})]^3}{[d(\text{istance})]^3},$$

$$\frac{T^2}{t^2} = \frac{D^3}{d^3},$$

here T and t are the periods (time) required for each revolution and D
ıd d are the mean distances, respectively, of any two planets. If we list
e periods and mean distances from the sun for a few of the planets

TABLE 20

	T (period) in earth years	D (mean distance)		T^2	D^3
		in miles	in astronomical units		
ercury.....	0.241	36×10^6	0.39	.058	.059
nus.....	0.615	67×10^6	0.72	.378	.373
rth.....	1.000	93×10^6	1.00	1.000	1.000
ars.....	1.881	142×10^6	1.53	3.538	3.560
piter.....	11.862	483×10^6	5.20	140.660	140.610

'able 20) and express the former in years and the latter in astronomical
its, the relationship is simpler. For the earth, t is one year and d is one
tronomical unit. If we substitute these values in the equation, then,

$$\frac{(T \text{ years})^2}{(1 \text{ year})^2} = \frac{(D \text{ astronomical units})^3}{(1 \text{ astronomical unit})^3}$$

d,
$$T^2 = D^3$$

· any planet, provided the period is expressed in years and the distance
astronomical units. This numerical relationship may be used to cal-
late one of these values for a given planet if the other is known. For

example, the period of revolution for Saturn is 29.46 years. What is i mean distance from the sun in miles?

$$D^3 = (29.46)^2$$

Hence $$D^3 = 867.8916$$

and, $$D = \sqrt[3]{867.8916} = 9.537$$

the distance from the sun to Saturn in astronomical units.

$$9.537 \times 92{,}870{,}000 = 885{,}600{,}000 \text{ miles.}$$

The Laws of Kepler apply not only to the motions of the planets, b also to those of their satellites. These laws, together with the princip of dynamics developed by Galileo and more completely by Newton, t how bodies move, but it remained for Newton to answer the question wh by combining them all into one great universal principle.

SUMMARY

1. Astronomy, the oldest of sciences, advanced concurrently with civilizatio
   (*a*)Primitive man probably developed a sense of *time* and *direction* by obs vation of *astronomical bodies and events*, but he associated them with superstitions.
   (*b*) The Babylonians and early Egyptians developed *observational astrono* and made *accurate computations and predictions*.
   (*c*) The Greeks with better instruments and more mathematics applie more developed *scientific method* to astronomy and developed a cosm raphy.
2. The Ptolemaic or geocentric system placed the earth at the center of the u verse with the planets and sun revolving around it. To explain retrogra motions of the outer planets *epicycles* were introduced. The planets w supposed to move in smaller circles (epicycles) around a point which mo in the planetary orbit around the earth.
3. The Ptolemaic hypothesis was finally rejected because it did not harmon accurately with the observations of Galileo and Tycho Brahe.
4. The Copernican or heliocentric system placed the sun at the center of solar system with the planets revolving about the sun in circular orbits. few epicycles were assumed to explain irregularities in planetary motion
5. Circular orbits with few or many epicycles were not in accord with the tensive and accurate observations of Tycho Brahe.
6. Kepler solved the dilemma by a revision of the Copernican system in wh he introduced elliptical orbits and other changes all of which are embodie his three laws of planetary motion:
   (*a*) Each planet moves in an elliptical orbit about the sun, with the sun at focus of the ellipse.
   (*b*) A line joining the center of a given planet with the center of the sweeps over equal areas in equal intervals of time.

(*c*) The squares of the periods of revolution of any two planets are directly proportional to the cubes of their mean distances from the sun.

. The development of a cosmography, like that of any other great theory, followed a cycle of observation, organization, and the formulation of an hypothesis. The cycle was then repeated with more observation by improved technique, organization, the rejection or revision of the old hypothesis and the formulation of a new or modified one.

STUDY EXERCISES

. Explain why astronomy is the oldest of the sciences.

. (*a*) Show that although the Babylonians and early Egyptians linked their astronomy with their superstitions they were scientific to a considerable extent. Do science and superstition wholly exclude each other?

(*b*) What tangible evidence do we have that these early astronomers made and recorded fairly accurate astronomical observations?

. Among the ancient Greek astronomers were Thales, Pythagoras, Eudoxus, Aristarchus, and Hipparchus. Mention briefly the contributions which each made toward the development of a cosmography, after first explaining the meaning of this term.

If the telescope had never been invented, is it likely that the Copernican system would have won universal acceptance?

Fill in the table by checking the system or systems for which each statement is true. The Geocentric or Ptolemaic system is represented by *G* in Column I, the Heliocentric system as set forth by Copernicus by *H*, Column II, and the modified, or modern, heliocentric system which followed Kepler's work by *M* in Column III.

	G	*H*	*M*
Sun approximately at the center of circular orbits.			
Sun at one focus of elliptical orbits.			
Earth at the center of the system.			
Epicycles required to explain retrogression; was accepted for the longest period of time.			
Few epicycles needed and only for irregular planetary motions.			
Two planets have orbits between earth and sun.			
Two planets have the center of their epicycles aligned with earth and sun.			
Requires that Venus and Mercury show phase changes.			
Requires a parallactic displacement of nearer stars relative to the more distant ones.			
Planets move around the sun with uniform speeds.			
Planets move around sun with variable speeds.			

6. On the first line mark *T*, if true, or *F*, if false. On the second line indica by 1, 2, or 3 which of Kepler's laws tells us whether or not the statement true.

.... (*a*) Jupiter is nearer to the sun than is Uranus and therefore has greater orbital speed.

.... (*b*) A line joining the center of the earth with the center of the s sweeps over equal areas during the months of June and July.

.... (*c*) The earth is nearest to the sun on or about January 1.

.... (*d*) A planet which is three times as far from the sun as the ea makes one revolution around the sun in 5.20 years.

.... (*e*) The distance from a given planet to the sun varies during its ye

.... (*f*) A planet has its greatest orbital speed at perihelion.

7. Was the heliocentric system revived by Copernicus because he discove new facts or was it because he considered it to be a better way to explain known facts?

8. Show that the discovery of the phase changes of Venus and the observatio a parallactic displacement of nearer stars relative to the more distant st are crucial points of evidence against the Ptolemaic system and for the he centric system.

9. Mark *A*, if the fact is explained by the geocentric system; *B* if it is explai by the heliocentric system; and *C* if it is explained by either system.

.... *a*) Day and night.

.... *b*) The retrograde motion of an outer planet.

.... *c*) The phases of Venus and Mercury.

.... *d*) The parallactic displacement of the stars.

.... *e*) The apparent change in size of Venus and Mercury.

.... *f*) The phases of the moon.

.... *g*) The apparent eastward motion of the sun among the stars.

10. (*a*) If a new planet with a period of revolution of eight years were fou what would be its mean distance from the sun in astronomical units? miles?

(*b*) If a new planet were found at a mean distance of 0.3 astronomical u from the sun, what would be its period of rotation in earth years?

11. State specifically what each of these scientists contributed to our present- cosmography:

(*a*) Ptolemy. (*b*) Copernicus (*c*) Galileo. (*d*) Brahe. (*e*) Kep

FOR FURTHER READING

1. Bartky, Walter, *Highlights of Astronomy.*

Chapter 5 treats celestial mechanics in language for the layman. The b includes important developments from the time of the ancients to Newton's for lation of the principle of gravitation.

2. Duncan, J. C., *Astronomy.* 4th edition; New York: Harper and Broth 1946.

Chapter 10 contains a very good discussion of the Ptolemaic and Coperni systems.

MAYER, JOSEPH, *The Seven Seals of Science.* New York: D. Appleton-Century Company, 1937.

The development of astronomy and related subjects are traced from the golden age of Greek learning through the establishment of the Copernican system. The author is broad in his point of view, and the entire book is easy to read. See especially Chapters II, III, and IV.

SEDGWICK, W. T., and H. W. TYLER, *A Short History of Science.*

Chapter X gives authentic historical material on the "new astronomy" and the beginning of modern science. This is an excellent reference book.

TAYLOR, L. W., *Physics, the Pioneer Science.*

Chapter 12 discusses Kepler's work and its significance in the initiation of the scientific era.

WOLF, A., *A History of Science, Technology and Philosophy in the Sixteenth and Seventeenth Centuries.* New York: The Macmillan Company, 1935.

This very fine, complete and well-illustrated book is recommended to those who are interested in the development of the great principles and theories of science. Chapters I, II, III, and VI deal with modern science and the contributions of Copernicus, Galileo, Brahe, and Kepler.

HARSÁNYI, ZZOLT, *The Star Gazer.* New York: G. P. Putnam's Sons, 1939.

A fascinating story of Galileo's long and fruitful life based upon authentic details of his great achievements in the physical sciences. The author displays a profound understanding of the intellectual forces at work in Italy and in other parts of Europe during this period. He handles in a deft and detached manner the much misunderstood differences between Galileo, who remained deeply religious, and the Church.

GALILEI, GALILEO, *Dialogues Concerning Two New Sciences.* Translated by Henry Crew and Alfonso De Salvia. New York: The Macmillan Company, 1933.

A recent translation of this great work of Galileo for the student who is interested.

14

Universal Force

THE DRAMA OF SCIENCE was now approaching what was perhaps its greate climax. Three thousand years of work and progress, with sometimes slo advances and sometimes even retreats, but, nevertheless, progress, we about to bear fruit. It is particularly fortunate that the two hundr years prior to Newton were years of extraordinary productivity. As show in the preceding chapter, Copernicus had successfully revived and p forth the heliocentric system. Galileo had made and used the first astr nomical telescope and had discovered important principles of dynamic Brahe's accurate observations had been analyzed by Kepler, who form lated the laws of planetary motion. In other fields equally importa advances had been made. Francis Bacon (*ca.* 1580–1626) had written the inductive method and had won great popular support for scienc René Descartes (*ca.* 1626–1650) had linked algebra and geometry, th forging another tool for science. William Gilbert had published h treatise on magnetism, *De Magnete* (1600), and William Harvey (*ca.* 161 1657) had discovered the circulation of the blood.

The year Galileo died another great genius, Isaac Newton (1642–172 was born. A brief summary of his life and achievements is given in Cha ter 1. We shall encounter his work frequently in this book, for his co tributions to the physical sciences are extensive and numerous. Ea in life he displayed extraordinary mathematical and scientific abilit and at the age of twenty-two, after receiving his B.A. degree at Trini College of Cambridge University, his career of discovery began. Duri the next two years, which he spent at his home in the country, Newt discovered the binomial theorem, laid the foundations of what is now t calculus, carried out experiments on light and color, formulated the La of Motion (Chapter 11), and started the chain of thought and investig tion which led finally to the formulation of the *Law of Universal Gravi tion.* This great principle was shown by Newton to be the mathemati consequence of his laws of motion and Kepler's laws of planetary moti and it was therefore the summation of the total work of mankind up that time in the fields of dynamics and astronomy. But it is more th

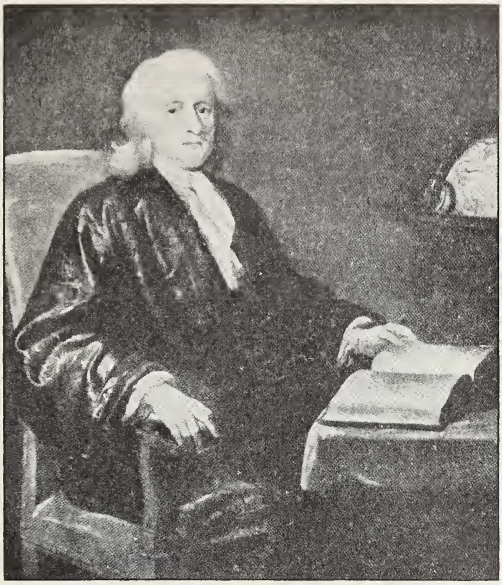


FIGURE 173. SIR ISAAC NEWTON
1642–1727
(*Courtesy of "Scripta Mathematica"*)

t, for this principle is a universal one and is not restricted to events on planet nor even in this solar system. We shall see how it was formud, how it was tested, and how it is applied.

Problem Formulated

/e have already seen that prior to Galileo the problem of dynamics to discover why thrown balls, projectiles, and even planets continue ıove. Rest was supposed to be the natural state of a body, and theremoving bodies required some kind of impelling force. Upon Galileo's overy of the important principle of dynamics later set forth in Newton's t Law of Motion, the problem changed completely. Since bodies in ion continue to move uniformly in a straight line, the problem for the ıtist was to find out, not why they continue to move, but why they ırt from uniform straight-line motion. For terrestrial events this ırture was satisfactorily explained (Chapter 12). When Newton gave ıttention to the motions of celestial bodies, he had already formulated aws of motion, he knew that the earth attracts bodies on or near it, he knew that the planets move in accordance with Kepler's laws.

The great problem for him was, therefore, to find why the planets a other celestial bodies depart from the straight-line motion and move Keplerian orbits. In other words, w does the planet at point *A* in its pa (Figure 174) move in the curved pa toward *C* instead of continuing in straight line toward *B*? The First L of Motion and the known behavior earthly projectiles gave the general a swer: each planet is acted on by an e ternal force. But what is this for In what direction does it act? Up what does its magnitude depend?

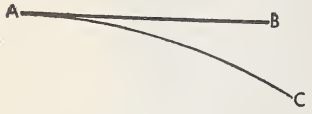


FIGURE 174
CURVILINEAR AND RECTILINEAR MOTION COMPARED
Planets move in curved paths.

The Problem Solved

It took the genius of Newton to conceive the idea that the same fo which acts on a falling apple, or which causes a projectile to deviate fr a straight path, holds the moon in its orbit. It will be shown in a la paragraph how he tested and verified this hypothesis. He further tended this hypothesis beyond the earth to the motions of the planets w reference to the sun. On the basis of his own laws of motion, and w great mathematical skill, he arrived at a number of inferences from Kepl laws:

1. *Each planet is acted upon by a force which is directed toward the s* He demonstrated mathematically that a body moving under the influe of a force directed always toward a fixed center obeys the Law of Ar (Kepler's second law). Conversely, the planets which obey this law each constantly subject to a force directed toward this center (the sun)

2. *The force of attraction between the sun and a given planet varies versely as the square of the distance between the two bodies.* Newton pro that for a body moving under the inverse-square law the orbit may be ellipse with the attracting body at one focus. Conversely, an ellipt orbit (Kepler's First Law) implies the inverse-square law for the force.

3. *The force of attraction is directly proportional to the mass of the pl* and is not in any way dependent upon the size, shape, composition, temperature. This inference was made from Kepler's Third Law and i harmony with the Second Law of Motion.

4. *The force of attraction is a mutual one* (Third Law of Motion).

Newton finally consolidated all his inferences into one general princ which applies not merely to the solar system but to the entire phys universe — the law of universal gravitation:

Every particle of matter in the universe attracts every other particle wi force which is proportional to the product of their masses, and inversely portional to the square of the distance between them.

e law is expressed by the proportionality:

$$F(\text{orce, gravitational}) \propto \frac{M(\text{ass})\ m(\text{ass})}{d(\text{istance})^2}$$

order to change this proportionality into an equality, the *constant of vitation G* (to be evaluated later) is inserted and the equation reads:

$$F = G\frac{Mm}{d^2}$$

ting the Theory

n order to test a principle of this kind, it is necessary to compare results ained by calculations based on the principle with those found experi- ntally. Twenty years before publication of his great principle, Newton ed his idea by a comparison of the force exerted by the earth on a ing body with that exerted by the earth on the moon. He tentatively med that the attractive force exerted by a body like the earth was cted toward its center, as if the entire mass of the body were concen- ed at that point. It follows that a falling body on the earth's surface pproximately four thousand miles from the center of attraction of the h and that the moon is sixty times as far away.

Ve may recall that according to the Second Law of Motion ($F = Ma$), force of attraction exerted by the earth on a body is in direct propor- to the mass of that body. If an apple and the moon were at equal ances from the earth, they would fall with equal accelerations. But the moon at a distance from the center of the earth sixty times that he apple, Newton reasoned, it should fall only $1/(60)^2$ of the acceleration with which apple falls. The experimental method of suring acceleration is to obtain the distance ered in a given time. During the first second apple falls 16.08 feet (one-half of its accelera-). Hence, if the inverse-square part of the of gravitation is true, the moon should be vn toward the earth

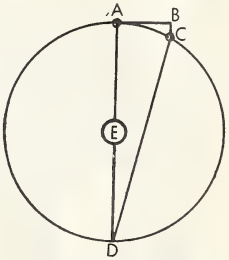


FIGURE 175
WHAT KEEPS THE MOON FROM FLYING OFF AT A TANGENT? THE ANSWER IS GRAVITY.

The moon "falls" toward the earth the distance BC while moving from A to C in its orbit.

$$60)^2 \times 16.08 \text{ ft} = \frac{16.08 \text{ ft}}{3600} = 0.00447 \text{ ft} = 0.0536$$

es in one second.

he actual deviation from a straight path or l" of the moon toward the earth may be cal- ted from observational data. In $27\frac{1}{3}$ days the n moves in its orbit around the earth E (Fig- 175) at a distance of approximately 240,000 s from E. For practical purposes we may

assume a circular orbit. While moving from A to C in one second (th drawing is not to scale) it also "falls," or deviates from a straight line, th distance BC. For the relatively short distance it moves in one second, th arc AC may be regarded as a straight line. Since the right triangles AB and ACD are similar,

$$\frac{BC}{AC} = \frac{AC}{AD} \quad \text{and} \quad BC = \frac{(AC)^2}{AD}$$

Now AC, the distance the moon travels in one second, is

$$AC = \frac{2\pi\,(AE)}{\text{seconds in } 27\tfrac{1}{3} \text{ days}} = \frac{2 \times 3.1416 \times 240{,}000 \text{ mi} \times 5280 \text{ ft/mi}}{27\tfrac{1}{3} \times 24 \times 3600 \text{ sec}}$$

$$= 3372 \text{ feet per second.}$$

$$\text{And } BC = \frac{(AC)^2}{AD} = \frac{(3372 \text{ ft})^2}{2 \times 240{,}000 \times 5280 \text{ ft}} = 0.00449 \text{ feet} = 0.0539 \text{ inches.}$$

The agreement between theory and observation is especially good in vi of the approximations assumed in the calculations.

Even after such excellent verification, Newton, uncertain as to the vali ity of his tentative assumption, withheld announcement of his discove It was only after he was able to prove that a sphere attracts external bod as if all its mass were concentrated at its own center that he could elabora his new principle and incorporate it in his renowned *Principia.*

The Constant of Gravitation

From the expression for the Law of Gravitation,

$$F = G\frac{Mm}{d^2},$$

it can be seen that any of the quantities may be calculated if the val for the others are known. The constant G may thus be evaluated. If M and m are each one gram and d is one centimeter, then $F = G$. That G is the force of attraction betw unit masses at unit distance apa but the great difficulty attend such a determination is that force of attraction between s small masses is so very slight tha cannot be detected. Hence, la masses must be used. An ingeni method was employed by Jolly, v used a double-pan balance (Fig 176). He placed five kilograms mercury in the spherical flask A accurately counterbalanced it

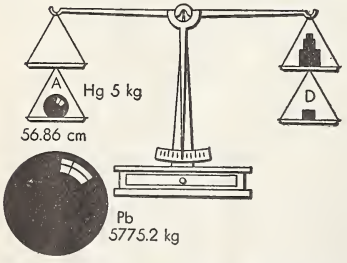


FIGURE 176. JOLLY'S METHOD OF DETERMINING THE CONSTANT OF GRAVITATION

ights in pan B. He then placed a sphere of lead C, weighing 5775.2 kg, ow the mercury at a distance of 56.86 cm (from center to center). A inite attraction was observed and was balanced by 0.589 mg on the n D. With these data G may be calculated. The force F is expressed dynes, and since one gram of force (weight) equals 980.3 dynes,

$$F = 0.000589 \text{ g} \times 980.3 \frac{\text{cm}}{\text{sec}^2} = \frac{G \times 5000 \text{ g} \times 5{,}775{,}200 \text{ g}}{(56.86 \text{ cm})^2}$$

ace,

$$G = 6.465 \times 10^{-8} \frac{\text{cm}^3}{\text{g sec}^2}$$

Lord Cavendish in 1798 used what is known as the torsion balance to ermine the same constant. Heyl, of the United States Bureau of ndards, has repeated the Cavendish experiment with improved appara- and technique and his latest value, announced in 1942, is

$$6.673 \times 10^{-8} \frac{\text{cm}^3}{\text{g sec}^2}.$$

s is one of our important constants. Others will be encountered. Two -gram masses placed one centimeter apart therefore attract each other h a force of 6.673×10^{-8} dynes.

Both the Jolly and Cavendish experiments are convincing evidence that ry particle of matter attracts and is attracted by every other particle.

ss of the Earth

Now we are ready to determine the mass of the earth. Any body whose s or weight we know or can determine may be used. For convenience, logram is selected. Its weight is the force with which the earth at- ts it — in other words, the force necessary to support a thousand- n mass (see Chapter 12) — and it has therefore a thousand grams of ght and represents a force of 1000×980 dynes. It is at a distance n the center of the earth equal to the earth's radius, or 6372 kilometers. e the gravitation constant is expressed in c.g.s. units, it is necessary xpress all quantities in those units.

$F = 980{,}000$ dynes

$G = 6.673 \times 10^{-8} \frac{\text{cm}^3}{\text{g sec}^2}$

$m = 1000$ grams

$d = 6.372 \times 10^8$ cm

$M =$ mass of earth in grams

stituting in the equation

$$F = G\frac{Mm}{d^2},$$

which may be rearranged to solve for M:

$$M = \frac{Fd^2}{mG} = \frac{9.8 \times 10^5 \text{ g cm/sec}^2 \times (6.372 \times 10^8 \text{ cm})^2}{1000 \text{ g} \times 6.673 \times 10^{-8} \text{ cm}^3/\text{g sec}^2} = 5.96 \times 10^{27} \text{ grams,}$$

or 1.314×10^{25} pounds, or 6.57×10^{21} tons, the mass of the earth.

The masses of the sun, of the other planets, and of some of the sta have also been determined on the basis of the laws of gravitation ar Kepler's laws. If the "fall" of the earth toward the sun is determined ju as we determined that of the moon toward the earth, this value may used to calculate the mass of the sun in terms of that of the earth. Sim larly, the combined masses of planets with moons, or of two stars revolvi about one another, or of any system in which one body revolves arou another under its gravitational force, may be determined.

Some Local Applications. Looking about us on this planet, we see ma examples of gravitational attraction, always between the earth and so other body of relatively smaller mass. Bodies fall, remain on the eart and have weight because the earth attracts them. But they also attra the earth. As this force of attraction between two bodies is a mutu one, it behaves, in effect, as a stretched rubber band or spring betwe two carts. The same force is exerted on the two bodies and gives t greater acceleration to the body of smaller mass. If an airplane with mass of twenty tons is falling to the earth, whose mass is 6.57×10^{21} to the earth will be given $20/6.57 \times 10^{21}$ or 1/328,000,000,000,000,000,000 the acceleration given the plane, and will move a proportionate distan Hence, the earth will be moved only imperceptibly by the falling body.

That the earth has a rugged surface with mountains and valleys d not change appreciably the direction of its force of attraction for bod external to it. Locally, however, a mountain does draw aside slightly plumb line, and this phenomenon was once used to estimate the mass the earth. As the scientist who made this determination had to estim first the mass of the mountain, his results were not highly satisfactory.

The fact that the earth is flattened at the poles and has an equato bulge (Chapter 4) has a number of consequences. The acceleration gravity and the weight of a given object vary over its surface in accorda with the law of gravitation. A mass weighing exactly one pound at equator will weigh more at one of the poles (Chapter 12). We now h the means of computing how much more. The earth's equatorial radiu 3963.34 miles, and its polar radius is 3949.99 miles. Hence, the wei of the object, increasing inversely as the square of the distance from center of the earth, becomes

$$1 \text{ lb} \times \frac{(3963.34)^2}{(3949.99)^2} = 1.0067 \text{ lbs}$$

if no other factors modify it. The centrifugal force due to the eart rotation is greatest in the equatorial regions and effects a slight additio

ease in the weight there, but is zero at the poles. For other objects on earth, even for those with masses that are great by our terrestrial dards, the mutual attraction is very slight, as shown by the Jolly and endish experiments. Large buildings, shops, or locomotives exert a risingly small attraction on each other even when close together. Let onsider one case. Two giant airplanes, each weighing thirty tons, are hundred feet apart, from center of gravity to center of gravity, in the The force of attraction between them may be calculated if we use constant of gravitation. Since this value is in c.g.s. units, the mass ie planes and the distance must be converted into those units.

$$30 \text{ tons} = 60{,}000 \text{ lbs}$$
$$60{,}000 \text{ lbs} \times 453.6 \text{ g/lb} = 2.72 \times 10^7 \text{ g}$$
$$400 \text{ ft} \times 30.48 \text{ cm/ft} = 1.22 \times 10^4 \text{ cm}$$

tituting in the equation:

$$G\frac{Mm}{d^2} = \frac{6.673 \times 10^{-8} \text{ cm}^3/\text{g sec}^2 \times (2.72 \times 10^7 \text{ g})^2}{(1.22 \times 10^4 \text{ cm})^2} = 0.332 \frac{\text{g cm}}{\text{sec}^2} \text{ or dynes.}$$

value is equal to 0.000012 ounces. The gravitational force of ction between the two planes is therefore only a little more than 0,000 of an ounce. If the planes are moved within two hundred feet ch other, the force of attraction is four times as great; if eight hundred part, it is one-fourth of the original value.

ght on the Moon

a body is transported to the moon, its weight due to the attraction e earth alone becomes only 1/3600 of its former value. But the moon attracts it much more than the earth does, for it is right on the moon's ce, within 1080 miles of the moon's center of gravity. In our calcu- ns of the moon's surface gravity, or the "moon weight," we shall e the earth's attraction. As the moon's radius is approximately one- h that of the earth, the weight of the body would be sixteen times as on the moon if the moon and earth had equal masses. The mass of arth, however, is 81.5 times that of the moon. Hence we have a r tending to reduce the weight of the body on the moon to 1/81.5 of on the earth. Combining the two and using more exact figures for adii —

$$\frac{1}{81.5} \times \frac{(3960 \text{ mi})^2 \text{ radius of earth}}{(1080 \text{ mi})^2 \text{ radius of moon}} = 0.165, \text{ or about one-sixth.}$$

is, the surface gravity on the moon is one-sixth of that on the earth. body would weigh only one-sixth of its earth weight on the moon. ctiles would attain six times the height they reach on the earth. tes could soar to new jumping records, and strong men who on the lift five hundred pounds could handle six times that mass.

The Precession of the Equinoxes

The equatorial bulge of the earth, together with its rapid rotati makes possible another gravitational effect, known as the *precession of equinoxes*. About 140 B.C., Hipparchus discovered that the equinox were moving westward at a very slow rate. The cause of this motion w not known until Newton, in his *Principles*, gave an explanation. As t complete story of the precession is a complex one, we shall limit our d cussion to a simplified discussion first of what it is and then of its caus

That the earth is tilted on its axis relative to the plane of its orbit, whi is the same as the plane of the sun's path among the stars, called t *ecliptic*, was discussed in Chapter 5. The plane of the earth's equa extended, which we call the *celestial equator*, makes an angle of 23.5° w the plane of the ecliptic, and the points where the two intersect are t equinoxes. In Figure 177 *AGBF* is the ecliptic and *CBDA* the celest equator intersecting at the equinoxes *A* and *B*. The earth is at *E* with axis extended to *N* also making an angle of 23.5° with the line *EH* p pendicular to the ecliptic.

The earth, in addition to its rotation, or spinning on its axis, and revolution, undergoes a slow movement known as *precession*. This mo ment is somewhat like that of a rapidly spinning top which slowly gyra but which always keeps the same angle between its axis and the fl The earth moves similarly, keeping the same angle of inclination, so t the plane of the celestial equator, which, of course, shifts with the ea still makes an angle of 23.5° with the plane of the ecliptic. But t points of intersection, or equinoxes, move. The equinoxes shift to B' a A', and the north celestial pole moves to N', but still is 23.5° from E

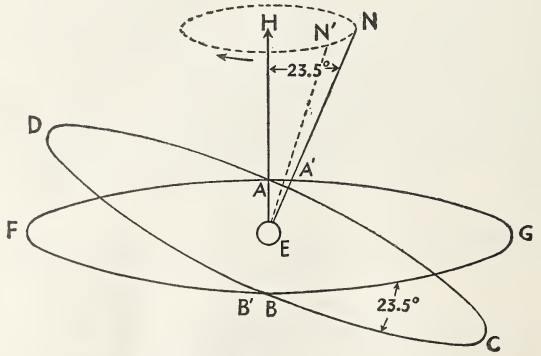


FIGURE 177. ILLUSTRATING THE PRECESSION OF THE EQUINOXES
Note the simultaneous gyration of the earth's axis. (*Compare with Figure 178.*)

his movement is very slow, however, amounting to only 50.2 seconds of ngle per year and requiring 25,800 years for a complete rotation. The xtended axis *EN* will in that time describe a cone around *EH*. Thus the quinoxes shift among the stars less than one minute of angle per year, nd the north celestial pole slowly moves, so that Vega will ultimately ecome our north star.

The cause of the precession of the equinoxes may best be understood if e consider again the spinning top (Figure 178). As it rotates rapidly n its axis, which is inclined to the oor at angle *a*, the force of gravity *G* nds to pull it downward. Instead falling, it moves sidewise, but eps always the same angle *a* be- ween it and the floor. The force which nds to tilt the spinning earth is the avitational attraction of the moon nd sun, but since the former is closer the earth, it produces the greater ect. The moon, which moves in arly the same plane as the sun, erts a greater pull on the bulge in e earth's equatorial belt than on the lar regions, thus tending to right e earth so as to bring the plane of equator into coincidence with its n orbit. So the effect on the pidly spinning earth is to cause it to change its position, just as a top es, but keeping the same angle between its equator and the plane of e moon's orbit. If the earth were perfectly spherical, there would be no ecession. If it did not rotate, it would not have retained its inclination. the moon and sun vary in their relative position with respect to the rth, the total force which they exert varies. The precession is, therefore, egular and complex.

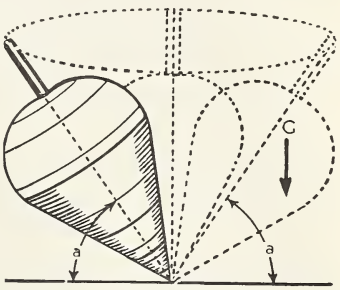


FIGURE 178. A SPINNING TOP IMITATES THE EARTH

It keeps the same angle with the floor while precessing in a circle. (*Compare with Figure 177.*)

e Discovery of Neptune

According to the Law of Gravitation, every particle of matter in the iverse attracts every other particle. The planets are each attracted by e sun, which they in turn attract, but each planet also exerts a mutual raction on all the other planets. The moon, which we are inclined to gard as under the total dominance of the earth, is attracted by the sun the extent that if the earth were to stand still, the sun would pull the on away from it. Since the planets change positions relatively to each ner and to the sun, as do also the earth, moon, and sun, the mutual ractions vary. The variations, though slight, cause small but definite

irregularities in the motions of these bodies. These departures from th orbits prescribed by Kepler's laws are known as *perturbations*, and thei prediction and observation are further confirmation of the Law of Universa Gravitation.

The discovery of the planet Neptune, perhaps the greatest triumph o mathematical astronomy, came as a direct result of the study of perturba tions in the orbit of the planet Uranus. After the discovery of Uranus, it orbit was determined and its motions carefully followed. After takin into account the perturbations due to the then known planets, there wa still a lack of agreement between the observed positions and those calcu lated — as much as two minutes of arc. It was suggested that the de partures from the calculated motion might be due to the presence of a mor remote and unknown planet. Two young men independently undertoo to solve the problem — J. C. Adams of Cambridge, England, and U. J Leverrier of Paris, France. After about two years of work, Adams, wh had begun before Leverrier, completed his calculations, but, before com plete observations had been made in England, the planet was discovere Leverrier, who in the meantime had completed his calculations, had im mediately sent his results to J. G. Galle in Germany. On the very nigh after he received the letter, February 23, 1846, Galle turned his telesco to the sky and in less than an hour found the planet within half a degr of the position calculated by Leverrier. Since the calculations of the tw men were in close agreement, both received equal credit.

The Significance of the Law of Gravitation

The period beginning with Copernicus and ending with Newton w probably the greatest in the history of science. Chaos and superstitio were replaced by order and scientific law. The knowledge of the pa was re-examined, much was rejected, and much was added. The Law Universal Gravitation was a revelation of the physical unity of the un verse — showing that all physical objects and events are related, a subject to the same law. It was the beginning of a new point of view whi has been very productive. Astronomy and physics have made great strid with the Newtonian mechanics as a tool. But even so, there is no end completion to scientific progress. New theories require extended obs vations, and new facts often require modification and even rejection theories — the cycle never ends.

And finally of great significance was the international character science during that fruitful period. The heliocentric hypothesis, original formulated by the Greeks, was revitalized by a Pole, and ably support by a great Italian genius, a Danish observer, and a German mathematicia Their results were formulated into one great universal principle by Englishman. Science knows no national, racial, or ideological boundari despite temporary interruptions.

SUMMARY

. The formulation of the Law of Universal Gravitation by Newton: Every particle of matter in the universe attracts every other particle with a force which is proportional to the product of their masses and inversely proportional to the square of the distance between them, and is expressed by the equation

$$F = G\frac{Mm}{d^2}.$$

. The principle of gravitation was verified by a calculation of the moon's actual "fall" toward the earth and comparing a value based on the principle.

. The gravitation constant was evaluated by Jolly and Cavendish. The latest figure is: $G = 6.673 \times 10^{-8}$ cm^3/g sec^2.

. The mass of the earth may be calculated by the use of the gravitation constant and the law of gravitation.

. The gravitational attraction between even very massive man-made objects, like ships or airplanes, is very small.

. The gravitational force or "weight" on the moon is one-sixth of that on the earth.

. The precession of the equinoxes is in reality the precession of the earth due to the gravitational pull of the moon on the earth's equatorial bulge. If the earth were not spinning or if it had no bulge there would be no precession.

. Calculations based on the Law of Gravitation, and with respect to the perturbations of the planet Uranus, led to the discovery of the planet Neptune.

. The Law of Universal Gravitation, the most important scientific principle ever formulated, had revolutionary and lasting effect upon human thought.

STUDY EXERCISES

. Check each item which is a direct consequence of the force of gravitation.

(*a*) .... weight
(*b*) .... mass
(*c*) .... atmosphere
(*d*) .... elliptical orbits of planets
(*e*) .... kick of gun
(*f*) .... effectiveness of armor-piercing bomb
(*g*) .... inertia
(*h*) .... satellites (moons)
(*i*) .... friction
(*j*) .... precession of the equinoxes
(*k*) .... effectiveness of a bullet

. The gravitational force of attraction between two bodies at a given distance from each other has a certain value. Below is listed a number of possible changes. Mark *A*, if the change increases the force of attraction; *B*, if the change decreases the force of attraction; *C*, if it does neither.

(*a*) .... Distance between the two bodies is increased.
(*b*) .... Shape of one is altered without changing the distance of its center of gravity from the other.
(*c*) .... One becomes fluid without altering the position of its center of gravity.

(*d*) .... The size of one of the bodies is increased without altering its tot mass or the position of its center of gravity.
(*e*) .... The mass of one of the bodies is decreased.
(*f*) .... They are put in motion, one around the other, without any othe change.

3. Check in the appropriate space if statement is true for the motion of the moo or for the motion of a projectile or for both.

	Motion of the moon relative to the earth	Motion of a projectile
(*a*) Has an initial uniform motion in a straight line.		
(*b*) Is pulled from straight line path by force of gravitation.		
(*c*) Path is an ellipse.		
(*d*) Path is a parabola.		
(*e*) Moves in accordance with the principle of independence of motion.		
(*f*) Follows Kepler's laws.		

4. Explain the meaning of the gravitation constant, G, assuming that u masses are attracting each other at a unit distance.
5. An apple at the surface of the earth falls from rest a distance of sixteen f in one second. How far would it fall in the first second if it were 12,0 miles from the earth's surface? How far would it fall in the second if it w 240,000 miles from the earth's center? (Use 4000 miles as earth's radius.
6. Refer to Figure 175, page 271.
   (*a*) Calculate the fall of the moon toward the earth in one second if the mo were twice as far away as at present.
   (*b*) Why may BC be regarded as the fall of the moon toward the earth?
   (*c*) In the geometrical proof, what two approximations are made?
7. (*a*) Given the gravitation constant, G (page 273), calculate the force of traction between two spheres of lead weighing one kilogram each a placed forty centimeters from center to center.
   (*b*) If the mass of one of the spheres is doubled, what is the force of traction?
   (*c*) If the masses of both spheres are tripled, what is the force of attracti
   (*d*) If the distance between the two spheres is tripled, what is the force attraction?
   (*e*) If the distance between the two spheres is reduced to twenty centimet what is the force of attraction?
8. If you were building a house at the foot of a large steep mountain, would y use a plumb line to make sure the walls are vertical? Explain.
9. What would a man weigh at the equator if his weight is one hundred a fifty pounds at the North Pole?

. The mass of the planet Neptune is approximately seventeen times that of the earth, and its radius is approximately four times that of the earth.
(*a*) If mass alone determined the surface gravity of a planet, what would a body which weighs one hundred pounds on the earth weigh on the surface of Neptune?
(*b*) The body on the surface of Neptune is how many times as far from the center of gravity of the attracting planet as one on the earth? This would have what effect on its weight if it were transported from the surface of the earth to the surface of Neptune?
(*c*) Combine (*a*) and (*b*) to calculate the weight of the one hundred pounds (earth weight) on the surface of Neptune.
(*d*) If "*g*" is 32 ft per sec per sec on the earth, what would it be on Neptune?

. (*a*) Briefly explain what is meant by *precession* and what causes it, using the spinning top as an example.
(*b*) By analogy explain how and why the earth undergoes a similar motion.
(*c*) Would there be any precession of the earth if it were perfectly spherical? If its axis were not inclined to the ecliptic?

. What are perturbations? Show how observation of them leads to the discovery of new planets.

. Write a paper of several hundred words on the life and achievements of Newton, pointing out particularly the importance and significance of his law of universal gravitation.

FOR FURTHER READING

. Lemon, H. B., *From Galileo to the Nuclear Age.*
Chapter 5 illustrates gravitational attraction by an imaginary trip to the moon.

. Mott-Smith, M., *This Mechanical World.*
Chapters XII and XIII provide a good summary of the main events leading to the development of the heliocentric system and the law of gravitation.

. Duncan, J. C., *Astronomy.*
Chapter 11 gives a more detailed and advanced treatment of gravitation and some of its effects. Includes tides and a discussion of the precession of the equinoxes on pages 108–111.

. Taylor, L. W., *Physics, the Pioneer Science.*
Chapter 13 takes up Newton's formulations of the great principle of universal gravitation. Historically accurate, interesting, and scientifically rigorous.

. Wolf, A., *History of Science, Technology, and Philosophy in the Sixteenth and Seventeenth Centuries.*
Chapter VII has a brief sketch of the life of Newton and a more advanced discussion of the development of the principle of gravitation.

. Sullivan, J. W. N., *Isaac Newton, 1642–1727.* New York: The Macmillan Company, 1938.
A biography which treats of Newton, the man, of his scientific work in a nontechnical manner, and of its far-reaching consequences.

15

The Moon

That orbed maiden with white fire laden
Whom mortals call the moon...
SHELLEY, *The Cloud*

THE MOON, the most conspicuous object in the night sky, has always bee a source of wonder and speculation for man. Because it is the closest all heavenly bodies, it appears to an observer on the earth to be almost large as the much more distant sun. To the astronomer its proximity and the consequent ease with which its surface may be studied, its comple motions followed, and its gravitational reaction to both earth and su observed, make it important. Its tidal effect on the earth has suggeste a number of absorbing problems concerning the past history of the eart moon system and interesting predictions as to the future of this syste To the poet its silvery disk has provided an inspiring subject for song; all men its tranquil light has always been welcome at night. To t superstitious and uninformed it is an important factor in weather, grow of crops, and even the state of the human mind.

Physical Data

With respect to the size of its primary planet, the earth, the moon is t largest of satellites. Its mean diameter is 2160 miles, which is more th one-fourth that of the earth. Its mass is 1/81.5 of that of the earth, 1/82.5 of that of the earth-moon system. The mean distance from t center of the earth to the center of the moon is 239,000 miles, or appro mately sixty times the earth's radius. The center of gravity of the eart moon system, therefore, lies within the earth's surface, $1/82.5 \times 239,0$ miles, or nearly 2900 miles, from the center of the earth. If support at this point, the two would balance each other. The density of the mo which may be calculated from the data given above with the density mass of the earth, is 2.4 grams per cubic centimeter. The methods measuring the distance to the moon and its diameter will be given Chapter 17.

ıases of the Moon

The moon is a dark body which shines only because it reflects sunlight. he face of the moon turned toward the sun is illuminated. As it travels ound the earth in its orbit, we see each month varying fractions of its uminated half, ranging from a thin crescent to the full disk. This wax- g and waning of the moon is one of the most easily observed of sky ıenomena. It has excited man's imagination and interest since early ıtiquity and was understood even on the basis of the Ptolemaic system. ɛt us see how the revolution of the moon around the earth causes the *'ıases* of the moon.

When the moon is in *conjunction* with the sun, that is, when the two have ıe same longitude, the moon is new. At this position, *A* in the diagram 'igure 179), the dark portion of the moon is turned toward the earth. he new moon rises and sets with the sun, and at noon the moon is on the eridian, as is also the sun, but the moon is not visible. After a day or two thin crescent becomes visible at *B*. When the moon is at or near the ɔw phase, its disk may be faintly illuminated by "earth-shine"; this light avels from the sun to the earth to the moon and is again reflected back the earth. A week later the moon is at the *eastern quadrature*, *C*, for its ngitude with reference to the sun is 90° east and the phase is the *first*

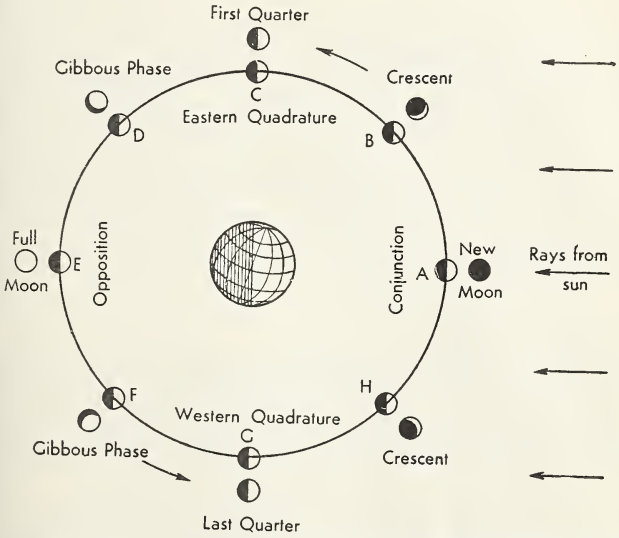


FIGURE 179. PHASES OF THE MOON AND THE CORRESPONDING POSITIONS IN ITS ORBIT

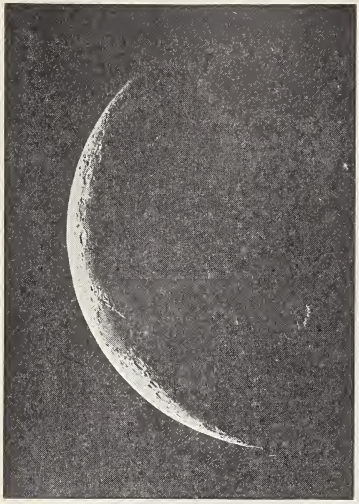


FIGURE 180. MOON AT AGE OF 3.85 DAYS (INVERTED)

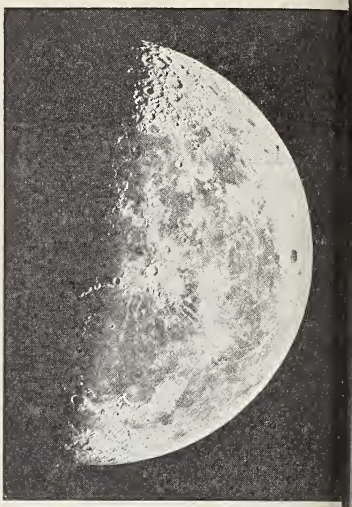


FIGURE 181. MOON'S DISK AT 22½ DAYS (INVERTED)

(*Courtesy of University of Chicago Press*)

quarter. We now see a half moon which rises about noon, crosses the m ridian, and sets six hours after the sun.

After passing through the more enlarged, or *gibbous*, phase, *D*, practical the full face of the moon is visible a week after the first quarter. Here t moon is in *opposition* with the sun, its longitude being 180°, so the *f moon* is twelve hours behind (or ahead of) the sun. As the sun sets, t full moon rises. After this the phases wane and successively pass throu the gibbous, the *last quarter* or *western quadrature*, and the crescent to t dark, or new, phase. The horns, or cusps, of the crescent moons alwa point away from the sun.

The Motions of the Moon

Revolution. The moon revolves around the earth, or, strictly speakin around the center of gravity of the earth-moon system, in an ellipti orbit with the earth at one of the foci. The orbit is an ellipse of l eccentricity and for practical purposes is a circle. The plane of this or almost coincides with the ecliptic, making with it an angle of 5° 9′ and c ting it at two opposite points called the *nodes*. The moon travels co pletely around the earth relatively to the fixed stars in an average peri of approximately 27⅓ mean solar days. This period is known as a *sider month*. To an observer on the earth, then, the moon moves eastwa

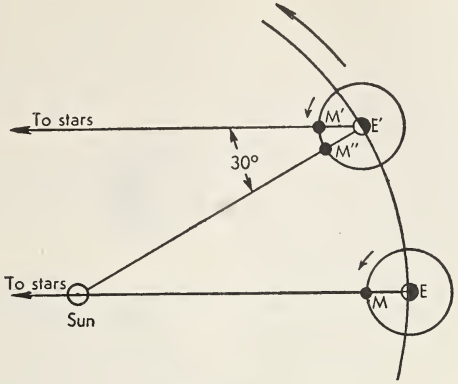


FIGURE 182

THE SIDEREAL MONTH (RELATIVE TO THE STARS) IS $27\frac{1}{3}$ DAYS
THE SYNODIC MONTH (RELATIVE TO THE SUN) IS $29\frac{1}{2}$ DAYS

The diagram shows where the difference occurs: the synodic month is longer than the sidereal by the time required for the moon to move from M′ to M″.

gainst the background of the stars at the average rate of $360°/27\frac{1}{3} =$ 3.2° per day.

The earth, around which the moon is revolving, is in turn revolving ound the sun, moving eastward in its orbit at the rate of approximately ne degree per day and completing its circuit in one year (Chapter 4). o the observer on the earth, the sun appears to move eastward against s background of stars at the same rate, one degree per day. Hence, if e measure the period of revolution of the moon with respect to the sun, e get a longer period, or month. While the moon is making its revolution ound the earth, our reference point, the sun moves ahead about thirty egrees and it takes the moon two more days to catch up with it. In the awing (Figure 182) the earth moves in its orbit from E to E' while the oon makes a complete revolution from M to M' in one sidereal month. n the meantime the sun has apparently moved ahead (owing to the earth's volution) relatively to the stars. In order to bring the moon, earth, and n into the same alignment as before, the moon must continue on to M''. his longer time interval is known as the *synodic month* and over a very ng period of time averages a little more than 29.5 days (the apparent onth).

Apparent Daily Motion of the Moon. We may recall that the solar day is e time required for a rotation of the earth with respect to the sun (Chapr 5). While the earth makes one rotation, the sun moves eastward one egree, and so the earth must rotate that extra degree in order to overtake

the sun. The time required is about four minutes, which is the difference between the sidereal (star) day and the longer solar day. We have an analogous situation in the rotation of the earth with reference to the moon. As the earth rotates the moon appears to rise in the east, move westward across the sky, cross (transit) the meridian, and set in the west. During a complete rotation of the earth, beginning when the moon, M, is on the meridian of the observer at A (Figure 183) and ending when the observer is back at the same position A with respect to the sun, the moon advances 12.2° to M' relatively to the sun. The earth must therefore rotate through an additional angle of a little more than 12.2° to overtake the moon. The time required for this additional rotation is, on the average, about fifty-one minutes. The moon, therefore, rises, crosses the meridian, and sets on the average fifty-one minutes later each day.

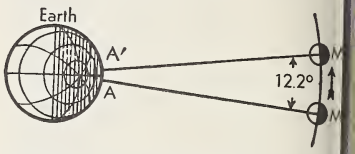


FIGURE 183. MOONRISE LAG AVERAGES 51 MINUTES EACH DAY

The diagram shows the reason: the moon advances in its orbit from M to M' while the earth completes one rotation plus the arc through which the moon advances.

Motion of Moon and Earth Relatively to the Sun. Could we observe the motions of the moon and earth about the sun from a point in space, they would appear quite different from what we might expect. In the first place, the moon and earth are approximately four hundred times as far from the sun as they are from each other. The path of the moon, therefore, nearly coincides with the orbit of the earth and, like that of the earth, is always circumsolar. In the drawing (Figure 184) the path of the center of gravity of the earth-moon system is represented by the solid line and that of the moon by the dotted line, though the deviation of the paths is exaggerated. The moon must, therefore, at times overtake and pass the earth, and at others be overtaken and passed by the earth. In all, the motions of the moon are extremely complex. Because the sun, earth, and moon are constantly changing their relative positions and each exerts a gravitational attraction, the moon's orbit is irregular and its speed like

FIGURE 184

The moon pursues a sinuous path around the sun as it revolves around the earth. Its path is always curved toward the sun.

rise subject to considerable variation. The calculation of the motion of ıe moon is one of the most complex and difficult tasks in the field of mathmatical astronomy. We therefore have limited ourselves to a discussion f the average motion and will consider but briefly one of its irregularities.

Rotation of the Moon. Almost exactly the same side of the moon is ırned constantly toward the earth; thus we see it today just as the ıcients saw it. It therefore makes one complete rotation in one sidereal ıonth, and its period of rotation is equal to the period of revolution. That such motion is rotation may be understood by a study of Figure 185. The moon moves successively through positions M_1, M_2, M_3, and M_4 with a point A on its surface always toward the earth. The point A, it may be seen, rotates around the axis of the moon or with reference to any fixed background like a star.

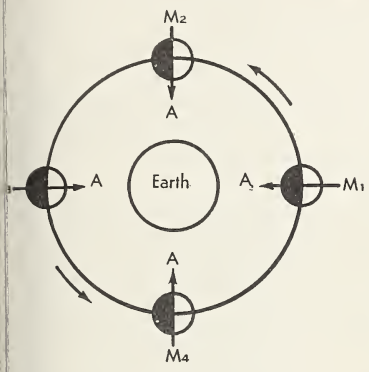


FIGURE 185

During each revolution around the earth the ›on rotates on its axis only once, keeping ne face toward the earth.
How often does it rotate in going around sun?
How often does the earth rotate in going ›und the sun?

We may conclude that in all his observations man has been and still is limited to exactly one-half of the surface of the moon. But, as a result of certain apparent oscillations which the moon undergoes during the month, we are permitted at various times to see other small parts, making in all 59 per cent of its surface. These oscillations, known as *librations*, are due to several causes. The inclination of the moon's equator to e plane of its orbit by an angle of about six and one-half degrees permits each month to see over and beyond the moon's north pole and two weeks er to see beyond the south pole. This is very similar to the inclination of e earth's equator to the ecliptic, a fact which causes the seasons. The ›on rotates at a uniform rate on its axis, but revolves at a variable rate accordance with the law of areas; hence there is some rocking back and th on its axis relatively to the earth. This combination of motions, erefore, permits us to see farther around the equatorial part of the moon. nally, since we observe the moon from various positions on the earth's rface and while it is rising and setting, we are able to see slightly beyond edges.

Eclipses

Solar Eclipses. If the moon revolved in the plane of the ecliptic, i would pass directly between the earth and the sun once every month a the new moon. The result of such a passage would be a total eclipse o the sun. But, since the orbit of the moon is inclined by 5° 9′ to the eclipti such an event occurs with less frequency, for the new moon is usuall above or below the sun. Twice a month the moon crosses the eclipti at the points called *nodes*. If the sun is in the direction of the node at th time, and the moon is new, we have a total eclipse; if it is near the directio of the node, we have a partial eclipse. As it takes the sun more than month to move through this region where eclipses are possible, the mo may make a revolution around the earth and pass the sun again durin this time. Thus, in a month we may have two solar eclipses, though n necessarily; and nearly six months later one or two more — but never mo than five per year.

Since the sun, our source of light, is a much larger body than either th earth or the moon, these two bodies cast conical shadows away from th sun. The dark cone $MM'E$ (Figure 186), in which there is no sunlight, the *umbra*, and the regions around it, MCA and $M'CB$, from which th light is partly excluded, constitute the *penumbra*. If MM' represents th moon and the dotted circle E the earth, then to an observer on the ear and within the umbra there will be a total eclipse of the sun. If th observer on the earth is located within the penumbra, he will observe partial eclipse of the sun. The distance from the earth to the moon vari considerably, so that we can now assume that the earth is at E' beyo the umbra. To an observer within the region of the extended cone at A the moon will be on the sun's disk, but smaller than the sun and with ring of light around it, producing an *annular* eclipse (Figure 188).

From the diagram it is obvious that the umbra sweeps across relative narrow portions of the earth, and so the regions from which a total eclip may be observed are small. Astronomers frequently travel great di tances to photograph a solar eclipse, so as to study the sun's corona a

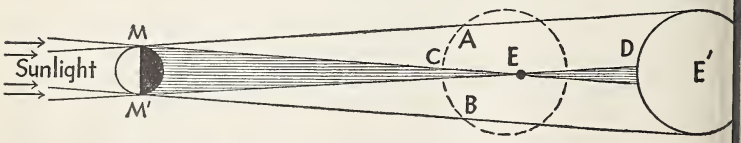


FIGURE 186. ECLIPSES OF THE SUN

An observer on the earth E and within the umbra MM′E will observe a total eclip within the region AB a partial eclipse. When the earth is beyond the umbra at E′ the server within the dark portion, extended, will observe an annular eclipse.

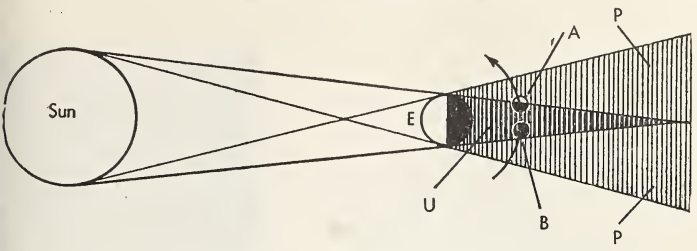


FIGURE 187. DIAGRAM SHOWING HOW THE EARTH ECLIPSES THE MOON
U = umbra; P = penumbra

search for planets in the region which is ordinarily obscured by the illiance of the sun.

Lunar Eclipses. When the earth passes between the moon and the sun that the moon lies within the earth's shadow, a lunar eclipse occurs. The oon is full and in opposition to the sun. But these relative positions are t enough to insure an eclipse, for the sun and moon must be near or on e opposite nodes. If the moon passes completely into the umbra (shown *B* in Figure 187), we have a total eclipse; if only partly (*A*), so that its sk is not entirely obscured, we have a partial eclipse. Lunar eclipses e not as frequent as solar eclipses. They may or may not occur during e year, and three per year is the maximum number possible. They last nger than a solar eclipse and are visible from all points on the earth's rface from which the moon may be seen. The maximum length for a tal solar eclipse is just a little less than eight minutes; a lunar eclipse may st for an hour and forty minutes.

The recurrence of eclipses was known to the ancients, who by studying ast performances concluded that they recur after an interval of eighteen ears and ten and one-third or eleven and one-third days, depending on e number of leap years. When an eclipse occurs, a similar one will ppear after this interval (the *saros*), but will not be visible from the same osition on the earth because of the one-third of a day in the interval. At ne end of this long period, which may be expressed as $6585\frac{1}{3}$ days, the n and moon return approximately to the same positions relatively to ne of the moon's nodes.

Close View of the Moon

Atmosphere and Temperature. Careful telescopic examination of the oon fails to show any evidence of an appreciable atmosphere. Observaon of planets with an atmosphere and a knowledge of phenomena assoated with the earth's atmosphere (page 86) tell us what we should find n the moon if air or moisture were there. But there are no clouds or

Second Contact
3 h 49 m 45 s p.m., C.S.T.
(The First Contact was 2 h 13 m 29 s p.m., C.S.T.)
A sun spot appears in the lower right-hand (southwest) quadrant.

Central Eclipse
3 h 53 m 00 s p.m., C.S.T.
The ring of light is the annulus, and represents the difference in size between the sun and the moon.

Third Contact
3 h 56 m 01 s p.m., C.S.T.
(The Fourth Contact was 5 h 17 m 04 s p.m., C.S.T.)
An enlargement of this photograph showed the "Baily's Beads," as bead-like breaks in the arc of the annulus where the moon is beginning to leave the sun's disk.

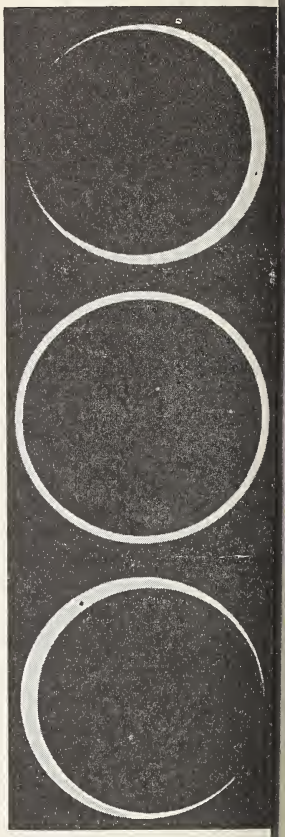


FIGURE 188
ANNULAR ECLIPSE OF THE S
(Courtesy of "Popular Astronom
Northfield, Minnesota)
From photographs made April
1940, by Dr. N. Wyman Stor

These pictures were taken with a Graflex camera through the 6-inch refractor of the Uni
sity of Kansas, the lens of the camera having been removed to let the image (about $\frac{7}{8}$-inch
diameter) fall directly on the photographic plate.

storms, no evidence of erosion, no twilight, refraction of light, or evidence of light scattering as in a haze. Shadows are absolutely black. During an eclipse of the sun the edge of the moon's disk appears sharp and dark, with no partly illuminated atmospheric ring. When the moon occults a star — that is, passes in front of the star — there is no gradual disappearance. The star suddenly vanishes behind the moon and a little later just as suddenly reappears on the other side of the moon.

If the moon were once a part of the earth, it must have had an atmosphere which has evidently left it. The velocity of escape for the earth is seven miles per second. That is, a projectile or a gas molecule must have that much initial velocity in order to leave the earth against its gravitational pull. Since the moon has considerably less mass than the earth, its velocity of escape is only 1.5 miles per second, which is greater than the velocities of gas molecules. However, the more energetic of the gas molecules in the upper part of the moon's atmosphere would gradually escape, others nearer the moon would take their place, and ultimately there would be none left. Certainly, if the moon ever did have an atmosphere, something like this must have happened.

The temperature of the moon's surface is one of extremes. During the two-week period of daylight when the sun is overhead, the temperature is probably above the boiling point of water (100° C.), but during the lunar night it drops to an extremely low point. During a total lunar eclipse the temperature was observed to drop from 70° C. to − 120° C. Such rapid cooling indicates that the surface rocks are very poor conductors of heat.

Surface Features. The portion of the moon's surface visible to observers has been carefully observed and photographed. It is very rocky and rugged, with numerous mountain ranges, isolated peaks, thousands of craters, and several relatively smooth plains. Many of these features were named by early observers. The chief mountain ranges are the Apennines, over four hundred miles long, the Alps, and the Caucasus. Most of them are short, narrow, and steep by terrestrial standards. Some of the peaks extend up as high as twenty-six thousand feet above the plains. The heights of the mountains are calculated by triangulation from the lengths of their sharp, dark shadows and the known position of the sun.

Other areas appear darker in contrast to the mountains and craters and were called *maria* (seas) by earlier observers, including Galileo. To the unaided eye or with low-powered telescopes, these relatively smooth surfaces appeared to be bodies of water. It is in these darker plains that the imaginative see the "man in the moon" and other figures.

The craters, of which more than thirty thousand have been mapped, are the most remarkable of the moon's features. The smaller ones resemble somewhat the volcanic craters on the earth, but the larger ones are great plains ringed by mountains, which may rise to heights of twenty thousand feet and have diameters extending to almost a hundred and fifty miles.

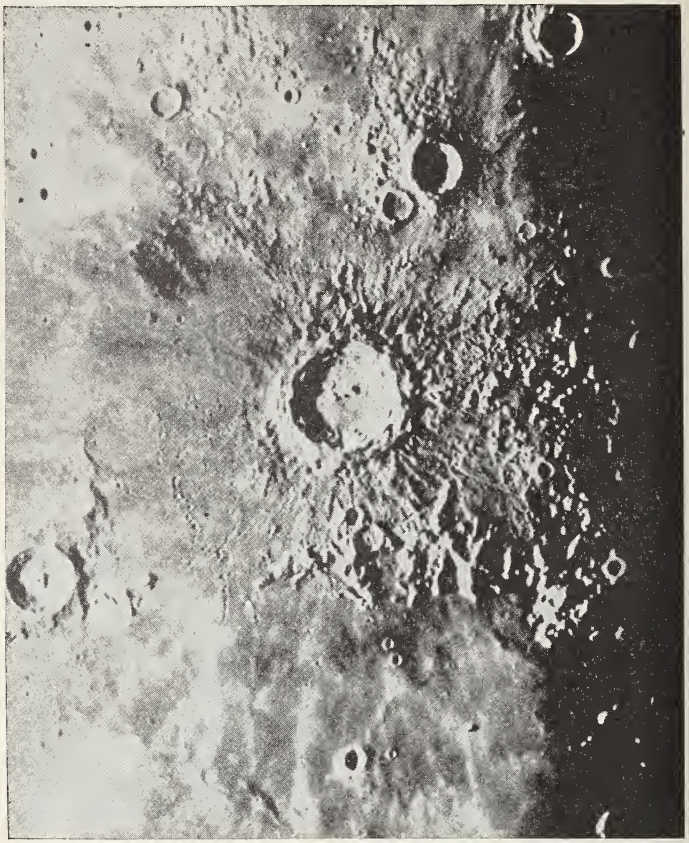


FIGURE 189. LUNAR CRATER COPERNICUS

(*Compare with Figure 181.*) *At the lower left is the crater Eratosthenes. Note t streams of lava surrounding Copernicus.* (*Photograph by Ritchey, Yerkes Observator Courtesy of University of Chicago Press.*)

The diameter of the crater Copernicus is fifty-six miles; that of Claviu one of the largest, is a hundred and forty miles. The origin of the craters is not known but two possibilities have been considered. Th first is that they were produced by volcanic activity. Their great siz the absence of great amounts of material which may have been ejecte and the total absence today of any indication of volcanic activity on th moon are plausible objections to this hypothesis. The other possibili is that the craters were produced by the impacts of large meteors. Th

reat meteor crater in Arizona, nearly a mile in diameter, is cited in upport of this hypothesis. That such features are not found all over the arth's surface could be explained by the erosive effects of our atmosphere nd water. One strong point against the meteor hypothesis for the lunar raters is their lack of the even distribution which one would expect in ccordance with the law of probability.

he Tides of the Ocean

Schedule of Tides. Along the shores of the ocean, waters rush in toward he beaches and inlets and out again at definite intervals. This periodic se and fall of the water level (not waves), some two to three feet in deep aters and hence not so apparent there as along the coasts, are known *tides.* The tides follow a time schedule which, although more complex, sembles that of the moon and to a less degree that of the sun. If there a high tide at a given place on the earth today, there will be another the same place tomorrow, but about fifty-one minutes later. On the xt day it will be still later by an additional fifty-one minutes. This terval, as we may recall (page 286), is the same as the daily lag in the sing and setting of the moon. But between these high tides at intervals twenty-four hours and fifty-one minutes, there is another high tide and o low tides. For example, high tide at 6 P.M. is followed by low tide at .13 A.M., high tide at 6.25 A.M., low tide at 12.38 P.M., and high tide again 6.51 P.M. There is actually considerable variation in the tide intervals er the earth, due to the moon's behavior and to differing local condi-ons.

Causes of Tides. It is evident that the moon's gravitational pull is the portant factor. In order to understand how it can cause the tides, we ust recall that the force of gravitation varies inversely as the square of e distance between the two bodies involved and that a rigid body re-

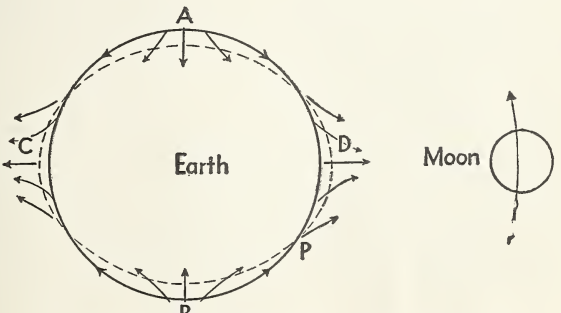


FIGURE 190. HOW THE MOON CAUSES TIDES

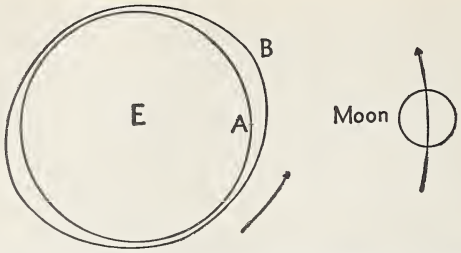


FIGURE 191. THE LAG OF THE TIDES BEHIND THE MOON

The earth drags the high tide B forward so that it is east of the moon. For an observer a A the high tide appears after *the moon's transit.*

sponds to gravitational attraction as if all of its mass were concentrate in its center of gravity. The solid portion of the earth is rigid, but no rigid enough to prevent slight earth tides; the water is mobile and eac particle of it may respond to gravitational pull. If we assume that th earth is completely covered with water, the tides will be high in region *C* and *D* and low in regions *A* and *B* (Figure 190). The water at *D* i nearer to the moon than is the center of gravity of the earth *E*, which i turn is nearer than the water at *C*. The gravitational force exerted by th moon is, therefore, greater at *D* than at *E* and greater at *E* than at *C* Since the water is not lifted away from the earth (the earth's gravitationa force is constantly in operation), the force exerted by the moon is effectiv in directions parallel to the earth's surface. The total effect is to heap u water on the sides of the earth at *C* and *D*, toward and away from th moon, and to draw it downward from *A* and *B*, leaving a belt of low tid round the earth between the regions of high tide. The water does no travel these great distances; the tides are cumulative effects of smalle movements.

As the earth rotates more rapidly than the moon revolves, the tide are dragged forward a little with the rotating earth. The high tides ar east of the moon instead of directly under it (Figure 191). The wate is not held in check by the moon, however, but only the tidal bulg or wave. At any given point *A* on the earth, therefore, the high tid appears at some time after the transit of the moon. This lag in tide is not constant over the earth. The varying depths of the ocean, shoals and shorelines all contribute to make the tides a very complex phenomenon In most places they are predictable only on the basis of long observations

The Sun as a Factor. The sun also acts independently to cause tides and these are at all times superposed on those caused by the moon. Whe the earth, sun, and moon are in alignment either at new moon (conjunc tion) or at full moon (opposition), the sun's high and low tides coincid respectively with those of the moon. The results are very high and ver

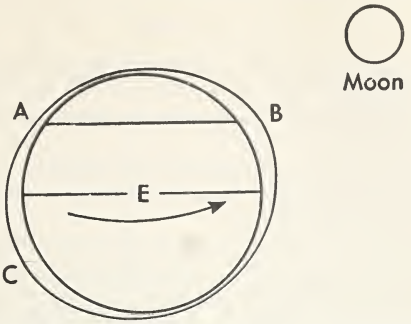


FIGURE 192. DAILY INEQUALITY OF HIGH TIDES

An observer at A experiences a higher tide at B twelve hours later. When moon is on the ane of the equator, E, the two daily high tides are equal.

w tides. These are called the *spring tides*. At the two quarters, when ıe moon and sun are ninety degrees apart as viewed from the earth, the ın's high tide coincides at a given place with the moon's low tide and ce versa. These tides, representing the difference between the effects moon and sun, and having a much smaller range, are known as *neap les.*

The mass of the sun is 27,600,000 times that of the moon, but it is)proximately four hundred times as far away. If we apply the principle gravitation we conclude that the gravitational effect of the sun on the rth is about 175 times that of the moon. Yet the sun's tidal effect is ly about 45 per cent of that of the moon. The reason for this is that ıce the moon is much nearer to the earth, the *difference* between its pull ı the water and on the earth is greater.

The tides show a daily inequality; that is, the two successive high tides ay be unequal. When the moon, M, for example, is north of the plane the equator E (Figure 192), the highest tides are at B and C. There is smaller high tide at A, but about twelve hours later, when the observer A is carried around to B by the earth's rotation, the high tide is greater.

Tidal Friction. The tides in shallow waters like the Bering Sea act as a ction brake in the earth's rotations. The loss of energy is extremely ght in proportion to the total rotational energy of the earth. The day lengthened, according to some calculations, one second every hundred ousand years. For this and other reasons it is estimated that the moon gradually receding from the earth about five feet every hundred years, d according to Kepler's third law its speed of revolution is slowly be- ming less. These data have been used to calculate backward in time in der to estimate the age of the earth (see Chapter 47).

SUMMARY

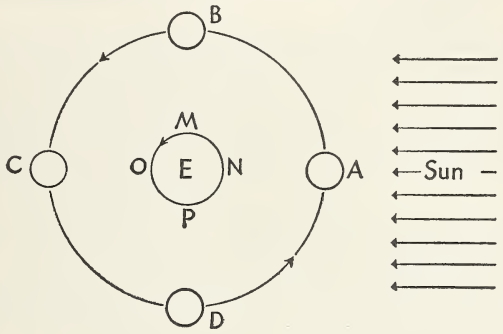
1. The phase changes of the moon as observed from the earth undergo a com plete cycle each month. At *conjunction* with the sun the moon is *new* an rises and sets with the sun; at *opposition* the moon is *full* and rises when th sun sets.
2. The motions of the moon are numerous and complex:
   (*a*) The moon revolves around the earth relatively to the stars in one *sidere month of 27⅓ mean solar days.*
   (*b*) The moon revolves around the earth relatively to the sun in one *synod month of 29½ mean solar days.* The difference in the lengths of the tw months is due to the orbital motion of the earth, which gives the sun a apparent eastward motion of one degree per day.
   (*c*) The daily rising and setting of the moon, owing to the rotation of th earth, occurs on the average fifty-one minutes later each day. This lag due to the orbital motion of the moon, which moves eastward around th earth at the rate of 12.2 degrees per day.
   (*d*) From a great distance the moon and the earth would appear to move i almost the same orbit around the sun, the moon taking a slightly sinuou path as it overtakes and passes the earth or in turn is overtaken by th earth. This motion, at the same time, amounts to revolution of the moo with respect to the earth.
   (*e*) The moon makes one rotation while it is making a single revolutio around the earth. One face is always turned toward the earth.
   (*f*) Owing to oscillations or *librations* of the moon and the slight inclinatio of its axis, we are permitted to see a total of more than one-half of its su face at different times.
3. Solar eclipses occur at new moon (conjunction) when the sun is in the direc tion of the node.
4. Lunar eclipses occur at full moon (opposition) when the sun and moon are o or near opposite nodes.
5. The moon has no atmosphere or moisture and therefore no erosion, twilight or haze. The temperature is one of extremes. Great craters, mountai ranges, and plains mark its surface.
6. Tides occur in the oceans of the earth at intervals which are in step with th lunar day. They are caused by the gravitational force of the moon aided c diminished by that of the sun. When in alignment the two bodies join forc to produce extremely high and extremely low tides. At the quarters there partial cancellation of the tidal pull and the tides are moderate. The form are the *spring* and the latter are the *neap* tides.

STUDY EXERCISES

. Refer to Figure 179 on page 283 and complete this table on the phases of the moon:

	Position	Rises and sets relative to Sun
New Moon	Conjunction	With the Sun
First Quarter		
Full Moon		
Last Quarter		

. In the diagram the moon is shown in four different positions, A, B, C, and D, relatively to the earth, E, and the sun. Observers M, N, O, and P are at four different positions on the rotating earth.



(*a*) Indicate the position of the moon at each phase by letters A, B, C, or D and give its age:
Moon is new at .... and is .... days old.
Moon is full at .... and is .... days old.
Moon is in third quarter at .... and is .... days old.
Moon is in first quarter at .... and is .... days old.

(*b*) Indicate by letters M, N, O, or P the position of the observer when:
.... the new moon is rising. .... the full moon is rising.
.... the new moon is setting. .... the full moon is setting.
.... the new moon is overhead. .... the new moon is not visible.
.... the first quarter moon is rising. .... the sun is rising.

(*c*) Indicate by letters A, B, C, or D the phase of the moon at which, for the observer on the earth, the moon:
.... rises and sets with the sun.
.... rises and sets 6 hours ahead of the sun.
.... rises and sets 6 hours behind the sun.
.... rises when the sun sets and sets when the sun rises.

Before each event or cycle of events place the letter identifying the time interval or time (right column) which corresponds to it:

.... Rising and setting sun	(*a*) Moon day
.... Neap tides	(*b*) Sidereal day
.... Daily rising and setting of stars	(*c*) Solar day
.... Revolution of moon about earth relatively to stars	(*d*) Synodic month
.... Solar eclipses	(*e*) Sidereal month
.... Spring tides	(*f*) Full and new moon
.... Lunar eclipses	(*g*) The quarter moons
.... Phases of the moon	(*h*) Full moon
.... Tides	(*i*) New moon

4. Which of these phenomena do not take place on the moon?

Erosion in general	Lithosphere tides
Rain	Ocean tides
Exfoliation	Day and night
Shooting stars	

5. According to calculation the sun exerts 175 times as much gravitational pu on the earth as the moon does. Explain why the tidal effect of the moon greater than that of the sun.

6. The sun's tidal effect on the earth is only 45 per cent of that of the moo Calculate how much greater the spring tide is than the neap tide at a give place.

7. Explain why we do not have a lunar eclipse and a solar eclipse at every revo lution of the moon around the earth.

8. Which of these statements are true, which false?
   .... The greatest tides occur when the moon is new or full and at perigee
   .... Annular eclipses of the sun may occur when the moon is new and at greater than average distance from the earth.
   .... Since the earth drags forward the high tides, they occur at a give place before the moon is overhead (crosses the meridian).
   .... The two successive high tides at a given place are equal.
   .... An eclipse of the moon occurs when the moon is full and near or on node.
   .... Two solar eclipses may occur in one month.

9. Refer to Figure 182 in answering the following questions:
   (*a*) What is meant by eastward direction among the stars — clockwise counter-clockwise when observed from the earth?
   (*b*) Does the sun actually move 1° per day with reference to the star Explain.
   (*c*) How long does it take for the moon to travel completely around the ear relative to our fixed guidepost, the stars? What is this time interv called? How many degrees, then, does the moon move eastward per da relative to the stars?
   (*d*) Explain why a longer interval is required for the moon to move arou the earth with respect to the sun, that is, from new moon to new moo What is such a time interval called? How many degrees does the mo advance each day with respect to the sun?

10. Refer to Figure 183, in answering the following questions:
   (*a*) What is the time interval required for one rotation of the earth relative to the sun?
   (*b*) During that interval how far does the moon advance? How long does it take the earth to rotate that number of degrees?
   (*c*) Explain on this basis why the moon rises, crosses the meridian, and sets approximately fifty-one minutes later each day.
   (*d*) What would be the disadvantage of using the lunar day, that is, the time required for the earth to rotate with reference to the moon?
11. The period of rotation of the moon is equal to the period of revolution. From a knowledge of Kepler's laws, which of these motions is irregular and variable? Explain other reasons why our view of the moon is not always restricted to 50 per cent of its surface. Can we see more than 50 per cent of its surface at any one time?

FOR FURTHER READING

1. Bartky, W., *Highlights of Astronomy.*
   All students will enjoy Chapter 4 on the moon. Written in a lively and fast moving style.
2. Baker, Robert H., *An Introduction to Astronomy.* Third edition; New York: D. Van Nostrand Company, Inc., 1947.
   Chapter VII is a well-illustrated and clear discussion of the motions of the moon, its physical features, and eclipses.
3. Skilling, William J., and Robert S. Richardson, *Astronomy.* New York: Henry Holt and Company, 1947.
   Chapter X is a first-class discussion of the common but rather complex phenomenon of the earth's tides.
4. Duncan, J. C., *Astronomy.*
   Chapters 6 and 7 give a detailed but understandable discussion of the moon and eclipses.
5. Whipple, Fred L., *Earth, Moon and Planets.* Philadelphia: The Blakiston Company, 1941.
   This excellent book is one of the Harvard series on astronomy. Chapters 7, 8, and 9 give a clear, accurate, and well-illustrated treatment of the moon, its influence on the earth, and its motions and a very fine discussion of its physical nature.

16

The Planets

AS LONG AS the Ptolemaic system was the accepted cosmography, man took great pride in his fancied position in the universe. He was the dominant being on the earth, which was, so he thought, the hub around which the planets, the sun, and the other stars revolved. With the development and acceptance of the heliocentric system, the earth was relegated to a position of relative unimportance. In general loath to accept this deflation, man was finally overwhelmed by the convincing evidence presented by that procession of great scientists whose work is described in Chapters 13 and 14. The earth, then, is just one of the planets, not the largest and not the smallest, moving around the sun in accordance with the same laws that govern the motions of the others. We find more to whet our pride in man's intellect and work — in the comprehension of the motions of the planets, for example — than in the mere astronomical position of the earth.

We have had a brief survey of the solar system and have studied in detail the earth and the moon. The motions of these bodies serve as a guide post for the study of the other planets and their satellites. After a more detailed study of the solar system as a whole we shall consider the motions of the planets and their individual characteristics.

The Solar System

Centrally located and dominating the solar system is the sun, whose mass is 332,000 times that of the earth and approximately seven hundred times that of all the rest of the solar system combined. We shall have occasion to study in detail this gigantic, luminous body (Chapter 18) and later (Chapter 47) to show that it is believed to be the parent body of the entire solar system. Rotating and revolving around the sun are nine planets. Each has its own period of rotation and each revolves in an elliptical orbit with the sun at one focus, in accordance with Kepler's laws.

Listing the planets in the order of their distance from the sun, we have Mercury and Venus, known by one classification as the inferior planets, the Earth, and the superior planets — Mars, Jupiter, Saturn, Uranus, Ne

TABLE 21

	Mean diameter in thousands of miles	Mass of earth = 1	Density of water = 1	Distance from sun in millions of miles	Period of rotation	Period of revolution around the sun	Number of satellites
Sun	864	332,000	1.4	..	25–33 days	....	..
Mercury	3	0.04	3.8	36	88 ? days	88 days	0
Venus	7.7	0.81	4.8	67	?	225 days	0
Earth	7.9	1.0	5.5	93	23 hr 56 min	365.25 days	1
Mars	4.2	0.11	4.0	142	24 hr 37 min	687 days	2
Planetoids	..	small	?	136–530	....	1.76–13.7 years	..
Jupiter	87	317	1.3	483	9 hr 57 min	11.9 years	11
Saturn	72	95	0.7	886	10 hr 15 min	29.5 years	9
Uranus	32.4	15	1.3	1,782	10 hr 45 min	84.0 years	4
Neptune	31	17	1.6	2,793	16 hr ?	165.0 years	1
Pluto	....	0.1 ?	?	3,670	?	248 years	0

une, and Pluto. By another grouping the first four — Mercury, Venus, Earth, and Mars — are designated as the inner planets and the remaining ve as the outer planets. Any attempt to show to scale the relative sizes nd distances of the planets and sun on one diagram is futile. If we epresent Mercury, the smallest and nearest planet to the sun, by a circle ne-eighth of an inch in diameter it must be placed one hundred and wenty-nine feet from the sun, whose diameter would be thirty-three nches. Pluto would be nearly two and a half miles away on the same scale. The drawings shown (Chapters 4 and 16) do not represent everything to cale. The table above gives the important data for the sun and each lanet.

Motions of the Planets

Five of the planets, Mercury, Venus, Mars, Jupiter, and Saturn, are isible to the naked eye. Although they shine by reflected sunlight, the lanets look like stars and are frequently referred to as "evening" and morning stars." They may be distinguished from the fixed stars by their anderings among the constellations and by their steadfast light in con rast to the twinkling stars. Through a telescope the nearer planets ap ear larger and disklike in contrast to the fixed stars, which appear as oints of light.

The orbits of the planets are ellipses and, in general, are of low eccen ricity or nearly circles. Mercury and Pluto move in more eccentric orbits as shown in Figures 193 and 195). The planetary orbits are nearly all in he same plane, none being inclined to the plane of the ecliptic (plane of the arth's orbit) more than 3.4°, except those of Mercury (7°) and Pluto 17.1°). These two planets are the nearest to the sun and the most re ote, respectively, and among the smallest. The planets revolve from

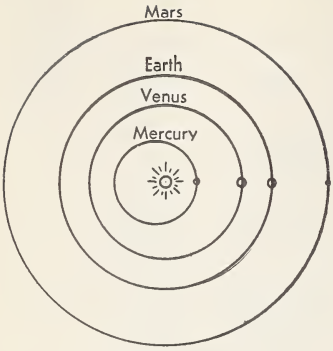


FIGURE 193
ORBITS OF THE INNER PLANETS
Note the eccentricity of Mercury's orbit. Distances to scale.

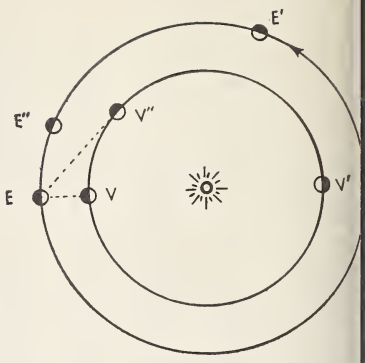


FIGURE 194
POSITIONS OF INFERIOR PLANETS
WITH RESPECT TO EARTH AND SUN

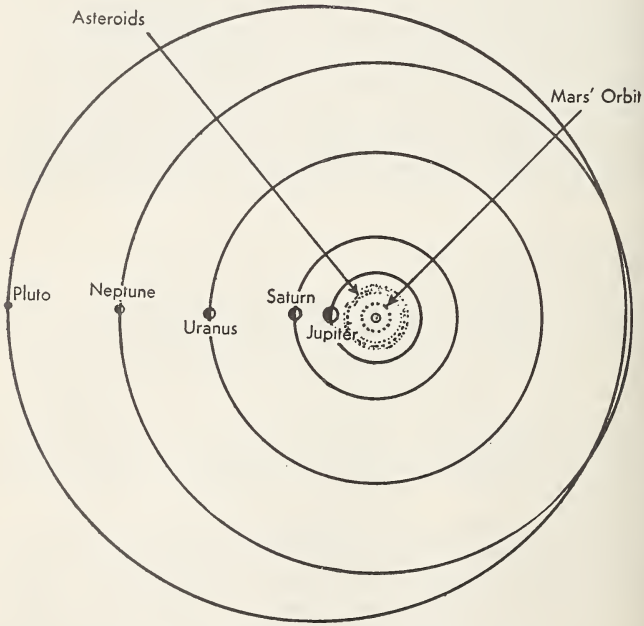
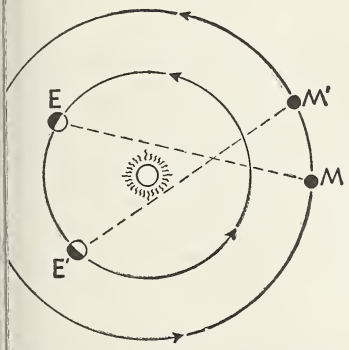


FIGURE 195. ORBITS OF THE OUTER PLANETS
That of Pluto is inclined 17.1° to the ecliptic and is so eccentric that at perihelion it nearer the sun than is Neptune. Scale is one-twentieth of that used for Figure 193.

st to east in almost circular orbits and practically in the plane of the iptic. All of them rotate from west to east except Uranus.

The *inferior planets*, Mercury and Venus, have shorter periods of revolun than the earth and to an observer on the earth appear to vibrate wly from one side of the sun to the other. They display the same phase anges as the moon (Chapter 13), but do not move through the same poions relatively to the earth and sun as the moon does. The moon revves around the earth; these planets revolve around the sun. Each inior planet may occupy two positions of conjunction, but none of opposin. The planet, which may be either Venus or Mercury, is in inferior njunction at position V (Figure 194) where it is between the earth and sun and in superior conjunction at V' where it is on the opposite side the sun from the earth. In both positions the elongation, which is the gle at the earth between lines drawn from the earth to the planet and to sun, is 0°. In other words, the planet is in the same direction from the th as the sun. When the planet is at V'' or in a corresponding position st of the sun, it is at its greatest elongation (angle VEV''), which is nsiderably less than 90° (always an acute angle).

The *superior* planets have longer periods of revolution than the earth, ich overtakes and passes them at intervals determined by their periods revolution. The apparent motion of such a planet as Mars, for example, s discussed in Chapter 13. The planet appears to move eastward relaely to the background of stars, to become stationary, and then to regrade for a time before moving eastward again. With respect to the , these planets appear to be continuously moving westward, although



URE 196. EXPLAINING THE APENT WESTWARD MOTION OF MARS

superior planet appears to an observer he earth to be moving westward (clock-) with respect to the sun.

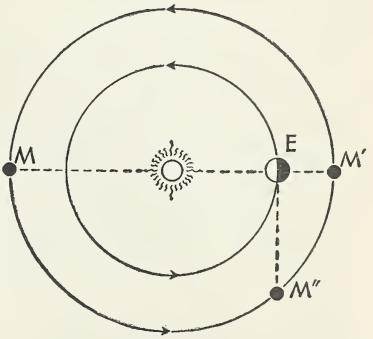


FIGURE 197

A superior planet may be in conjunction or in opposition or have an elongation of 90°.

at an irregular rate (Figure 196). While the earth moves from E to E' Mars moves a little more than half of the angular distance from M to M' By sighting Mars at M from the earth at E and again from E' to M', i appears to have moved westward (backward) with respect to the sun.

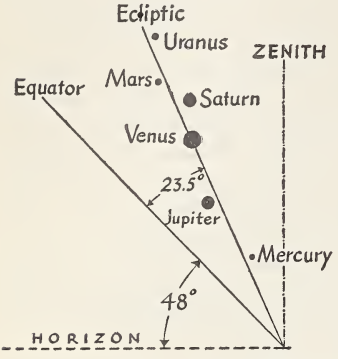


FIGURE 198. A RARE COINCIDENCE

Six planets visible at the same time at latitude of New York or Chicago.

A superior planet is never in inferio conjunction, but may go through th entire range of elongation from 0° t 180° as shown in Figure 197. At M the planet is in conjunction with 0 elongation, and at M'' it is at easter quadrature. At M' it is in opposition with an elongation of 180°; that is, i is just opposite in direction to the su as observed on the earth.

When a planet is visible above th horizon at sunset, it is called a *evening star*; when it is above th horizon at sunrise, it is called a *morn ing star*. Since each planet has its ow orbit and period of revolution, it i usual for many of them to be visibl at the same time. An unusual displa of all of the planets visible to the unaided eye was seen during the latte part of February, 1940. Mercury, Jupiter, Venus, Saturn, and Mars an if a telescope was used, Uranus, were visible as evening stars, the first fiv within a spread of 39° (Figure 198).

Mercury

Mercury, for which there were recorded observations as early as 2 B.C., is an unusual planet in many respects. It is the nearest to the su and, therefore, of all the planets, receives the greatest amount of radia energy from that body and in accordance with Kepler's Third Law of M tion is the fastest moving. Since Mercury is so near the sun, it is difficu to see, except when it is in the vicinity of its greatest elongation, whi ranges from 18° to 28°. It is most conspicuous as an evening star at su eastern elongations as may happen to occur in March and April; as morning star at such western elongations as may occur in September a October.

The eccentricity of its orbit is very great; at perihelion it is 28,550,0 miles from the sun, and it moves with an orbital velocity of thirty-s miles per second; at aphelion, one-half of its year later (forty-four day it is 43,350,000 miles from the sun, and has an orbital velocity of twent four miles per second. Markings which some astronomers claim to ha seen on Mercury do not appear to change their position on the planet

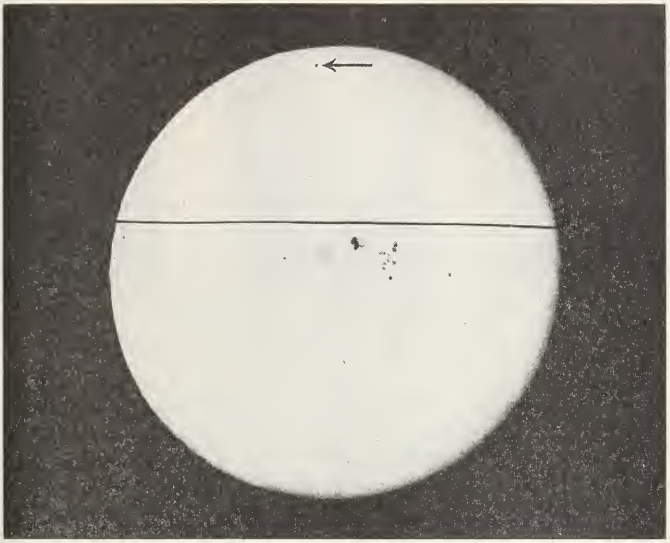


FIGURE 199. TRANSIT OF MERCURY ACROSS THE DISK OF THE SUN, NOVEMBER 14, 1907
(*Photograph by Fox, Yerkes Observatory*)

k. This would indicate, although the evidence is far from conclusive, at the planet always presents the same face to the sun and that the period rotation is the same as the period of revolution, eighty-eight days. The nperature on the sunlit face is probably as high as 400° C., while that on e dark side must be very close to absolute zero (− 273° C.). Owing to e inclination of its orbit to the ecliptic, Mercury does not pass directly tween the sun and the earth — that is, transit the sun's disk — at every erior conjunction. This occurs only about thirteen times in a hundred ars. The last transit of Mercury was on November 11, 1940, and the xt one will be on November 14, 1953. Observed through a telescope ring transit, Mercury appears as a small black dot with a sharp clear- t edge which indicates that the planet has no atmosphere.

enus

Venus is the brightest and most conspicuous object in the sky, with the ception of the moon and the sun. Its brightness is due to its relative oximity to the sun and to the observer on the earth, as well as to its re- cting surface. About 59 per cent of the light which strikes it is reflected. is frequently visible during daylight and at night is bright enough to st shadows. After superior conjunction (*V'* Figure 194), it moves east-

FIGURE 200. PHOTOGRAPHS OF VENUS
(*Exposures in ultra-violet light by Ross at Mount Wilson Observatory, June 6, 24, and 26, 1927*)

ward from the sun and may be seen as an evening star above the horizo in the west at sunset and sets after the sun. It continues as an evenin star until it approaches inferior conjunction (*V*, Figure 194). After pas ing westward from the sun, it appears in the morning sky as the mornin star, rising in the east before the sun and completing the cycle at superi conjunction. Since the planet completes its revolution in 225 days, th earth must lag behind it, and Venus completes the cycle described abov by gaining one lap on the earth. The average time required for this 584 days.

Like Mercury, Venus exhibits all the phases and it may be recalled tha the full phase observation by Galileo (Chapter 13) proved to be cruci evidence against the Ptolemaic hypothesis. Venus resembles the earth size, in density (see Table 21), and in the possession of an atmospher It appears to be covered with a layer of white clouds (Figure 200). Du ing the last transit of this planet over the sun's face on December 6, 188 a halo of light appeared around its disk. This phenomenon, together wi the extension of its ends when it appears as a crescent, indicates the pre ence of an atmosphere. The next transit of Venus will occur on June 2004. The period of rotation has not yet been determined, as no markin are visible on its surface. From other evidence it appears that it has rath a long one, but that it does not always present the same face to the sun

Mars

Mars is the reddish or orange-colored planet about which so much co troversial material has been written. As the first of the outer planets, revolves around the sun, outside of the earth, in 687 of our days, at a mea distance of 141,500,000 miles from the sun. Its distance from the ear varies widely. At conjunction the average distance from the earth is ov 234 million miles; at opposition it is close to forty-nine million miles. Sin the planet's orbit has a fairly high eccentricity, it comes even closer to t

arth when opposition occurs near the planet's perihelion. On July 27, 939, it came within 36,030,000 miles of the earth, its closest approach in fteen years. In some respects Mars resembles the earth, although smaller nd less dense (see Table 21). Permanent markings observed as early as ne seventeenth century have permitted accurate measurement of its period f rotation, which is 24 hours, 37 minutes, 22.58 seconds. The equator of Iars is inclined to its orbit by 24°. It is flattened at the poles more than ne earth.

Finer details, some of which appear to change, were first observed by chiaparelli in 1877–79. These were long and narrow dark lines, called *nali* or channels. Unfortunately this term was translated as "canals," nd since this term suggests engineering feats, highly intelligent Martians ere postulated for their performance. The existence of these canals is ne of the major controversies of astronomy. Let us consider the facts. here are seasonal changes on Mars, for the planet is tilted, and there are imatic zones. The seasons are twice as long as the earth's seasons, and ne Martian temperature is lower (30° C. to considerably below zero) than nat of the earth. From its reflection of sunlight, the presence of some ind of material which forms the polar caps, and the appearance of faint louds, the existence of an atmosphere is established. The atmosphere is ery thin, and there are indications of water vapor and oxygen, but in nuch smaller quantities than in the earth's atmosphere. The polar caps lso undergo seasonal changes. During the long Martian summer, in its outhern hemisphere, the polar cap becomes very small and on occasion

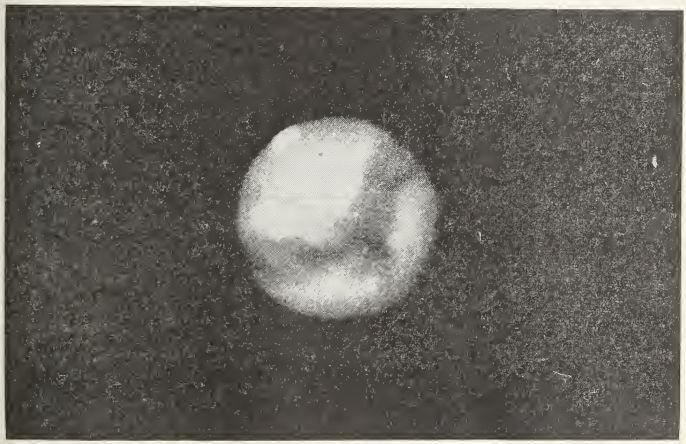


FIGURE 201. MARS, REGION OF SYRTIS MAJOR
(*Photographed by Barnard at Yerkes Observatory, September 28, 1909*)

has entirely disappeared; during the winter in the same hemisphere, th ice cap becomes very large — larger than the winter cap of the northern hemisphere. The southern hemisphere, therefore, which is the upper on on the inverted image of the photograph (Figure 201), has the greater ex tremes of climate. The dark markings, which appear grayish or greenish become darker and greener during the Martian summer and becom brownish or fade out during the winter. The general light and reddish surface of the planet does not change. These variations of color hav been studied in great detail with the aid of various filters to utilize infra red, ultra-violet, and some of the visible radiation.

As to the canals, various claims have been made. Percival Lowell an his associates have mapped out several hundred canals or markings, many converging on points or *oases*, and some running parallel to each other They have inferred that these markings are watercourses constructed by intelligent beings, who are forced to drain the polar caps and to conserv their dwindling water supply (the velocity of escape on Mars is two and a half miles per second). Most astronomers do not agree with this inter pretation. They agree that something is there, as indicated by the mor apparent markings, and it is quite possible that there are large river valley bordered by vegetation or mountain ranges eroded down to low relief The smaller markings, which appear to be long and straight, may be th combination of other details not resolved by the telescope.

It is both interesting and stimulating to speculate on the possibility o life on Mars or Venus. That plant life exists on Mars is thought to b possible. From our knowledge of life on this planet with its many form and adaptability to a wide variation in conditions, it is not difficult to pic ture plant and even animal life under still other conditions. That suc life must be similar to life on the earth does not necessarily follow. A to the possibility of beings on other planets, it is purely speculative, fo there is no evidence.

The two satellites of Mars, Deimos and Phobos, were discovered in 187 They are both very small, the outer one, Deimos, being about one-half th size of Phobos, whose diameter is estimated to be ten to fifteen miles These satellites are the smallest celestial bodies visible to us and are ver useful in the determination of the mass of Mars. Phobos is unique in tha its period of revolution is less than Mars' period of rotation. This satellit as observed from Mars, therefore rises in the west, moves eastward acros the sky, and sets in the east.

Jupiter and Its Moons

Jupiter is the largest of all planets, and also the brightest with the ex ception of Venus and at times Mars. Its diameter is approximately eleve times and its volume thirteen hundred times those of the earth. Its mas which is roughly only one-thousandth of that of the sun, is greater than th

FIGURE 202. JUPITER

Photographed in ultra-violet light by Ross with the 60-inch reflector at Mount Wilson Observatory, August 20, 1927. Courtesy of University of Chicago Press.)

mbined masses of all the other planets. In shape it is very oblate, with polar diameter about one-fifteenth less than the equatorial diameter. his is not surprising, in view of its extremely high speed of rotation, the riod of which is less than ten hours. Its equatorial speed is therefore arly thirty thousand miles per hour. The equatorial region appears to mplete its rotation in a little less time than the regions of higher latitude. he period of revolution of Jupiter relative to the stars is 11.86 years.

Along the equatorial region of Jupiter is a great light-colored belt, somehat irregular, and varying in width from seven thousand to ten thousand iles. On each side are dark belts of reddish-brown color and these are ralleled by others of different tints which become less conspicuous in gher altitudes. These belts vary in number and width from year to ar and even change from day to day. There are other markings of a mi-permanent nature. In 1878 appeared a large oval spot about twenty-ve thousand miles long and more than eight thousand miles wide. It on became a deep red and after a few years began gradually to lose its lor. It has disappeared only to reappear a number of times, and in its sence leaves what is known as the great red spot hollow.

The low density of the planet (1.34) suggests an extensive atmosphere, t its low surface temperature (− 140° C.) rules out the possibility that e belts consist of clouds of water vapor. On the other hand, their anges, although sluggish, exclude the likelihood that the material in them rooted to any solid portion of the planet. Little is known of the content

of this atmosphere. Ammonia and methane have been identified. It has been suggested that the planet has a dense rocky core and that the clouds or belts consist of droplets or crystals of ammonia floating in a sea of methane gas.

The satellites of Jupiter have played important rôles in the history of astronomy. When Galileo used his telescope for the first time in 1610 (Chapter 13), he discovered the four largest — Io, Europa, Ganymede, and Callisto. There are eight more satellites, the last discovery having been made in 1951. The first five satellites move in almost circular orbits, nearly in the plane of the planet's equator and orbit. Jupiter's equator is inclined to the plane of its orbit only 3° 7′. The eighth, ninth, and eleventh satellites revolve in the retrograde direction from east to west. Two of the satellites are larger than the planet Mercury. It was Roemer who in 1675 found from observations of the four largest satellites that light travels with very great but measurable velocity.

Saturn and Its Rings

To the naked eye, Saturn, the most remote planet known to the ancients, appears as a yellowish star. Through a telescope, it is one of the most beautiful and interesting of all celestial bodies. A great system of concentric rings, encircling the planet in the plane of its equator and with the outer limit 86,300 miles from its center, makes it unique and beautiful. Galileo was the first to see these rings, but he thought they were two other

FIGURE 203. SATURN

(Photographed by Barnard with the 60-inch reflector at Mount Wilson Observatory, November 10, 1911)

lanets on either side of Saturn. These rings are neither solid nor fluid, ut probably consist of independent particles. It has been suggested that hese particles may be the residue of some other body, perhaps a satellite, /hich came too close to Saturn and was disrupted. There are three rings, he middle one being the brightest and the inner, or *crepe* ring, the least right. They are probably not more than ten miles in thickness (Figure 03).

Saturn is almost as large as Jupiter and has surface features very much ke those of Jupiter. Its period of revolution is 29.5 years and its period of otation is 10 hours, 14 minutes, 24 seconds; like Jupiter, it has a slightly onger period at higher latitudes. Like Jupiter, too, it appears to have a ery deep atmosphere, with a low surface temperature of about −150° C. ts equator is inclined to the ecliptic nearly 27°.

Saturn has nine satellites, all of which revolve outside of its rings and ost of which revolve in orbits that lie almost in the plane of the rings. he smallest satellite, Phoebe, which is less than two hundred miles in iameter, revolves in a retrograde direction from east to west.

Uranus

Uranus was discovered in 1781 by Sir William Herschel, who thought he ad found a comet. Later, after close observation of its motion, an at-empt to calculate its orbit as a comet proved it to be a planet. Through ne telescope it appears as a bluish-green disk, and it is believed to resem-le Jupiter and Saturn physically, although smaller, with a diameter about our times that of the earth. Uranus revolves in an orbit which is inclined o the plane of the ecliptic only 1°.

Uranus has four satellites, rather difficult to observe because of the great istance of this system from the sun and earth. If we assume that the atellites revolve in the plane of the planet's equator, then this plane is in-lined to the plane of the planet's orbit 98°. However, some regard it that he inclination is 82°, and that Uranus rotates and its moons revolve back-ard.

Neptune

The dramatic discovery of this planet was discussed in Chapter 14. lthough extremely remote, its diameter has been estimated to be a little ss than that of Uranus. The existence of its one satellite permits the etermination of the mass of the planet and of its inclination. Its satellite evolves in the retrograde direction.

Pluto

A careful study of the motions of Uranus and Neptune indicated to Per-ival Lowell the possibility of an ultra-Neptunian planet. The planet as sought, not by telescopic observation, but by a thorough search of

photographs of that part of the sky. In 1930, C. W. Tombough found th image of the new planet. As photographs dating back to 1919 recorded th position of the planet, calculations of its path, its distance from the sur and its period of rotation were made. Pluto, which is the name assigne to the new planet, is probably smaller than the earth. Its high inclinatio and eccentricity have been noted. In the vicinity of its perihelion, Plut is nearer to the sun than Neptune.

Planetoids

The planetoids (dwarf planets) or asteroids are small, planet-like bodi which revolve around the sun as members of the solar system. Most them move in the space between the orbits of Mars and Jupiter. The firs of these bodies was discovered by Piazzi, an astronomer in Sicily, in 180 and was named Ceres. Within a few years three more were discovered an given the names Pallas, Juno, and Vesta. The latter is the only planetoi that at times is visible to the unaided eye. Since the middle of the la century, many more have been found by telescopic search. The mode method was inaugurated in 1891 by Wolf of Heidelberg, who has mad more than five hundred discoveries. Wolf used cameras with large ape tures driven by clockwork to follow the stars across the sky in the region the ecliptic. With long exposures, the stars give round images, but th asteroids produce lines or trails.

Important among the planetoids is Eros, discovered in 1898, because comes within less than fourteen million miles of the earth. This bo provides astronomers with a means of accurately measuring the distan from the earth to the sun and other astronomical distances. The large asteroid, Ceres, has a diameter of four hundred and eighty miles. Mo asteroids, however, have diameters under sixty-five miles; many are t small to measure. Over fourteen hundred with known orbits are liste and it is estimated that there are over a hundred thousand of these bodi with a total mass of possibly one-two-thousandth of that of the eart Within the last few years several planetoids have been found which co very close to the earth's orbit. Adonais, discovered by Delporte in 19 passes within a little more than a million miles of the earth's orbit, a Hermes, discovered by Reinmuth in 1937, passes within less than a milli miles of the earth.

The origin of the planetoids is unknown. It has been suggested that th might be the fragments of a shattered planet, but it is impossible to a count for the present orientation of their orbits on the basis of this hypoth sis. Another hypothesis, which is in accord with our theories as to t origin of the planets (Chapter 47), is that the asteroids are the fragme of a planet which might have been formed had it not been for the distu ing gravitational influence of Jupiter.

Comets

The spectacular and often unexpected appearance of comets, so unlike the other objects in the sky, has always aroused great interest and often fear. They appear in the sky moving in no particular plane, sweep around the sun, and recede. Their visits have been regarded as portents, and even the cause of such human disasters as wars, plagues, and famines.

Comets are members of the solar family moving in extremely elongated elliptical orbits in accordance with Kepler's laws. The larger ones consist of a starlike *nucleus* surrounded by a cloudlike, nebulous mass called the *coma* (Gr., *hair*), which often extends as a long, filmy, streaming tail that may be more than a hundred million miles in length. Only the nucleus of the comet, which seems to consist of solid particles, appears dense enough to obstruct light. Stars may be seen through the tail, which has an extremely low density, far below that of the highest vacuum we are able to achieve in the laboratory. The tail is usually turned away from the sun and is probably formed as a result of electrical repulsion or radiation pressure exerted by the sun. Part of the light given off from the comet is reflected sunlight, yet the coma and tail appear as a glowing gas. This may be due to absorption and emission of radiant energy from the sun.

About one thousand comets are known, and more are discovered every year, some by amateur astronomers. They are named for their discoverers. On February 3, 1942, announcement was made of the discovery of the Whipple comet. This comet, visible with a small telescope, crossed paths with the moon on March 2, 1942, about the same time as a total lunar eclipse. One of the great comets is named for Halley, an associate of Newton. Applying Newton's principle of gravitation to the motion of this comet, which appeared in 1682, Halley showed that it had an elliptical orbit and on the basis of records of its visits as far back as 240 B.C. predicted its return in 1759. The comet appears every 75.5 years, and its next return is predicted for 1985 (Figure 204). Just prior to its last appearance in 1910, the many newspaper stories about its close approach to the earth and a possible collision caused some apprehension. The earth, at this time, passed through the tail of the comet, but the only effect observed was a slight iridescence of the sky. It is likely that a head-on collision of the earth with a comet would do no more than shower us with myriads of shooting stars which would disintegrate in the earth's upper atmosphere.

Meteors

Meteors are small solid particles that move swiftly through space and are not visible unless they enter the earth's atmosphere. Then they appear as shooting stars, for their average velocity is thirty miles per second and they are heated by the friction of the air. Most of them are burned or vaporized in the upper atmosphere and do not reach the earth. It is esti-

FIGURE 204. HALLEY'S COMET, JUNE 6,1910

Shows a discarded portion of the tail drifting away from the comet. The diameter of th head at this time was 320,000 miles, and its distance from the sun 110,000,000 miles When first seen in September, 1909, the head was only 140,000 miles in diameter, its distanc from the sun 200,000,000 miles. In April, 1911, the diameter had dwindled to 30,00 miles at a distance of 400,000,000 miles from the sun. (*Courtesy of University of Chicag Press*)

nated from observations that more than twenty million meteors strike the arth's atmosphere daily. The average height at which they are observed s seventy-four miles (page 87).

Some meteors of greater mass are not all consumed in their contact with he atmosphere and parts of them survive to reach the earth. These odies are known as *meteorites*. Their speeds are so reduced in passing hrough the air that those of smaller masses scarcely penetrate the ground. Those of larger masses do not suffer such a reduction in speed and bury hemselves in the earth. Before striking the earth's atmosphere, these odies are at an extremely low temperature, possibly near absolute zero. n the few seconds required for their passage through the atmosphere to he earth, the excessive heat which strips off their outer portions may not enetrate to their interior. Some are found to be only warm when they trike the earth; others are very cold.

The meteorites we usually see in museums are metallic, consisting of an lloy of iron and nickel with traces of other elements. Others are com- osed of an iron-nickel sponge with silicate minerals filling the cavities. third group, known as stony meteorites, contain a large percentage of agnesium and silicon oxides with other terrestrial elements and a little on and nickel. All contain gases.

Great meteoric showers were observed in 1799 and in 1833, and recur- nce was predicted for every thirty-three and one-third years. While hose occurrences in 1866, 1900, and 1933 were numerous, they fell short f the previous showers. Some very large meteorites have been found. he largest single meteorite on exhibit was brought back from Greenland

FIGURE 205. AERIAL VIEW OF METEOR CRATER NEAR WINSLOW, ARIZONA
(Courtesy of University of Chicago Press)

by Admiral Peary and is at the American Museum of Natural History i New York City. It is a thirty-six-ton mass of iron-nickel alloy. A hug mass, possibly one hundred and twenty-five by three hundred by thre hundred feet, is reported to have been found buried in the sands of th Sahara Desert. Meteor Crater (Figure 205), near Winslow, Arizona, is great cavity six hundred feet in depth and nearly a mile in diameter. Thou sands of fragments of meteoric iron have been found in the vicinity. At tempts are being made to locate the huge meteorite which some think i buried beneath the southern wall of the crater.

The origin of meteors is still a matter of speculation. Chemical analyse of them have yielded no new elements, and their composition is very muc like the estimated composition of the earth (page 210). The fact tha streams of meteors travel around the sun in orbits resembling those o comets suggests that the meteors are the remains of disrupted comets.

SUMMARY

1. The solar system consists of nine planets, twenty-eight satellites, and man planetoids, comets, and meteors, all moving around the sun.
2. The inferior planets, Mercury and Venus, may each occupy positions of in ferior and superior conjunction with respect to the earth and sun. Thei greatest elongation (angle at earth made by planet and sun) is always a acute angle.
3. The superior planets may occupy positions of superior conjunction and oppo sition. Their elongation may vary from 0° to 180°.
4. Mercury appears as both morning and evening star. It transits the su about thirteen times in a hundred years. Mercury is the smallest planet an the nearest to the sun.
5. Venus appears both as morning and evening star. Like Mercury it exhibit all the phases.
6. Mars resembles the earth somewhat and has markings on its surface whic vary from time to time. The possibility of life on Mars, for which there is n evidence, has been much discussed. Of its two satellites, Deimos and Pho bos, the latter revolves around Mars faster than the planet rotates.
7. Jupiter, the largest of the planets, has eleven satellites, three of which re volve in a retrograde direction. Jupiter's great belts and clouds are o interest.
8. Saturn with the great rings has nine satellites. Uranus, with four satellites is inclined to the plane of its orbit 98°. Neptune is of interest because of it dramatic discovery. The orbit of Pluto, the most remote of the planets, i inclined to the ecliptic more than is that of any other planet. Owing to th great eccentricity of its orbit, Pluto is sometimes nearer to the sun tha Neptune.
9. The planetoids or asteroids are small planet-like bodies, most of which ar found moving in the space between Mars and Jupiter.

. Comets consist of a starlike nucleus and a nebulous tail. They have always aroused great interest and, at times, fear.

. Meteors are small solid bodies that move rapidly through space, sometimes striking the earth's atmosphere, where, heated by friction, they appear as shooting stars. Portions which survive to reach the earth are called meteorites.

STUDY EXERCISES

. What two points of difference enable an observer to distinguish between planets and stars?

. (*a*) List the planets in the order of their distance from the sun.

(*b*) List the planets as indicated below:

The smallest.	The one whose orbit is most inclined to the ecliptic.
The largest.	Those which transit the sun.
The nearest to the sun.	The one having the greatest orbital speed.
The most remote.	The one which crosses its neighbor's orbit.
The one having the most eccentric orbit.	

. (*a*) Check in spaces to indicate if statement is true of inferior planets, superior planets, or both.

	Inferior Planets	Superior Planets
May be in inferior conjunction		
May be in opposition		
May be in superior conjunction		
Elongation is always an acute angle		
Elongation may range from 0° to 180°		

(*b*) Fill in the number of degrees:

When a planet is in inferior conjunction its elongation is ....°
When a planet is in superior conjunction its elongation is ....°
When a planet is in opposition its elongation is ....°

. Consult a current monthly sky map and prepare a drawing showing the location of the visible planets. Locate these in the sky and note their relative change in position after a week and after a month.

. Mark *T* if statement is wholly true, and *F* if any part of the statement is false.

.... If the orbit of Mercury were in the plane of the ecliptic, it would transit the sun every eighty-eight days.

.... To an observer on Venus the earth would at times appear to move backwards.

.... The rings of Saturn mark approximately the plane of its equator.

.... As Mars is inclined to its orbit at about the same angle as the earth to its orbit, the seasons on Mars should be of the same length as those on the earth.

.... One of the planetoids has approached nearer to the earth than any other body.

.... Life (if any) on a planet like Mercury, whose period of rotation is equa to its period of revolution, would be forced to occupy the edge of it illuminated face.

6. Check the factors which are of importance in considering the possibility o life, as we know it, on another planet:

Mass	The presence of Moons
Seasons	The presence of water
Period of rotation as compared with period of revolution	Polar ice caps
	Length of year
Kind of atmosphere	Velocity of escape
Average temperature	

7. The mass of Jupiter is 317 times that of the Earth and its diameter is eleve times that of the earth. Calculate the acceleration of a falling body near it surface.

8. Check in spaces if statement is true of the bodies listed:

	Planetoids	Comets	Meteo
At times shine by their own light			
Shine by reflected light			
At times come in contact with Earth			
Move in accordance with law of gravitation			
Part is repelled away from the sun			
Move mostly in region between Mars and Jupiter			
Add to mass of Earth			
May be observed at times without telescope			

9. In what position may Mercury or Venus be best observed from the earth?
10. In what position may the superior planets be best observed from the earth When in such a position, at what time will it appear on the meridian?
11. Under what circumstances is a planet known as an evening star? As morning star?
12. The satellite of Mars, Phobos, has a period of revolution which is less tha Mars' period of rotation. Make a drawing and indicate how this satellit might appear to move, to an observer on Mars.

FOR FURTHER READING

1. Bartky, W., *Highlights of Astronomy.*
Chapter IV gives a well-organized discussion of all members of the solar fa ily, their motions, and relative positions.

2. Duncan, J. C., *Astronomy.*
Chapters 12 and 13 in this widely-used text deal with the planets, meteor and comets.

3. Baker, R. H., *An Introduction to Astronomy.*
Chapters IX, X, and XI tell the story of the planets, comets, and meteors a way which is vivid and easily understood.

4. Baker, Robert H., *Astronomy.* New York: The Macmillan Compan 1939.
Chapters VII, VIII, and IX contain a more detailed treatment of the plan

and their motions, of meteors, and of comets. The book is written in a brilliant and understanding fashion. The illustrations are excellent.

. WHIPPLE, F. L., *Earth, Moon, and Planets.*
Chapters 10, 11, 12, and 13 contain a clear, accurate, and well-illustrated discussion of the planets.

. WATSON, FLETCHER G., *Between the Planets.* Philadelphia: The Blakiston Company, 1941.
This little book, another of the Harvard series on astronomy, is entirely devoted to a consideration of asteroids, comets, and meteors. The treatment is nonmathematical yet scientific and very fascinating.

. JONES, H. SPENCER, *Life on Other Worlds.* New York: The Macmillan Company, 1940.
Modern astronomy has revealed that there are millions of stellar systems. Is the earth the only home of life? The author describes the conditions on the other planets and answers this question in so far as it is possible to do so at present.

17

The Astronomical Yardstick

ONE OF THE GREAT INTELLECTUAL ACHIEVEMENTS of modern science ha
been the discovery of methods for measuring the distance to such bodies a
the sun, the planets, and the stars, to get reliable data on the dimen
sions of our universe. Thus far all our discussions pertaining to th
planets and solar system have avoided reference to the methods used t
measure astronomical distances. The great spiral nebula in Andromed
for example is so far away that its light reaches the earth only after nin
hundred thousand years. This is not a fanciful guess, but is based o
sound observational data. Since early times man has been trying to answe
the question of the size of the universe. Astronomers have had a patter
of the solar system since the days of Kepler. The Third Law of Kepl
made possible precise calculations of the relative distances from the eart
to the moon, to the various planets, and to the sun. But this gave onl
a vast blueprint without an absolute scale of measurement. The situatio
was analogous to having the blueprint of a house without any measur
ments indicated on it. The various dimensions of the house would be in
dicated correctly, but only on a relative scale. If the height of a door, fo
example, was translated into feet and inches, then the measurements o
the entire blueprint could be determined. In a similar way the patter
of the solar system, based upon Kepler's Third Law, could not be inte
preted until at least one measurement within the entire blueprint could b
made with precision. Then, also, there was the larger problem of the rel
tion of the solar system to the rest of the universe, which involved the que
tions of the distances to the stars and the size of the universe. The diff
culty of the problem may be seen from the fact that the distances to th
nearest stars were not determined until 1838. The purpose of this chapt
is to show how the ingenuity of astronomers, coupled with persistence o
effort and a familiarity with the language of space and time, has evolve
a yardstick for the measurement of astronomical space. The problem wa
of such complexity that it had to be solved in three steps: (1) the dete
mination of the size of the earth; (2) the determination of the size and di
tance to the moon; and (3) the determination of the size and distance t
the sun.

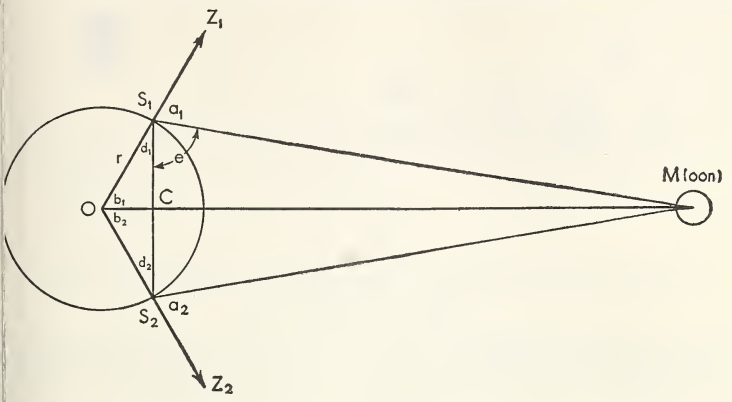


FIGURE 206. THE DISTANCE TO THE MOON

The method used to solve the first problem, that of the diameter of the rth, has already been described in Chapter 4. There we learned that the ean radius of the earth has been found to be 3958.82 miles. It is now be- ved that the error in this important distance does not exceed a hundred d fifty feet. Hipparchus, the inventor of trigonometry, successfully termined the distance and size of the earth's companion, the moon. He nsidered the distance to be thirty-three and two-thirds times the diameter the earth, and its diameter one-third that of the earth, the true figures ing 30.2 and 0.27, respectively. The values of Hipparchus could not be own with greater accuracy until modern developments made possible eater accuracy in the measurement of angles. Modern telescopes now ake it possible to obtain angular measurements precise to 0.05 seconds of arc. The essence of the method of Hipparchus can be seen in Figure 6.

ze and Distance of the Moon

S_1 and S_2 in Figure 206 are two observatories on the earth, which for nplicity are assumed to be the same distance from the equator. Observ- s in each station measure precisely the distance the moon is below the nith at each station at a given time. Thus the angles, a_1 and a_2, known the zenith distances, are measured. The angles b_1 and b_2, and the lati- des of S_1 and S_2 are known. The following relationships, then, will be ue:

Angle d_1 is known: $180° - (90° + b_1)$, and
Angle e is known: $180° - (a_1 + d_1)$.

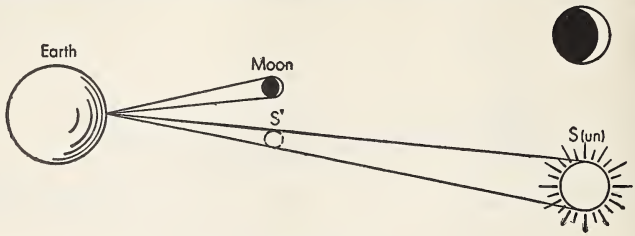


FIGURE 207

The moon and sun have nearly the same angular size. (Drawing not to scale.)

Then, S_1C can be calculated: $S_1C = r \sin b_1$. The radius of the earth r i accurately known. Also,

CO can be calculated: $CO = r \cos b_1$, and
CM can be calculated: $CM = S_1C \tan e$.

Finally, the mean distance from the center of the earth to the center of th moon is given by $CO + CM$. Thus, by trigonometrical methods, th moon's mean distance has been found to be very nearly 238,900 miles Note that an essential part of the calculation is the mean radius of th earth. The footrule, then, for measuring astronomical space, is the radiu of the earth.

Like all two-body systems in motion around a common center, the pat of the moon in its orbit is an ellipse. Thus, the actual distance of the moo varies from 222,000 miles when at perigee — minimum earth-moon distanc — to 252,000 miles at apogee — maximum earth-moon distance.

When a precise value for the moon's distance is known, it is relativel easy to determine the moon's radius by measuring the apparent size of th moon in degrees — its angular diameter. The apparent size of an object i space depends both on its size an distance. For example, the angula sizes of the moon and sun are ver nearly the same, 31 min 5 sec arc for the moon and 31 min 59 s for the sun. But the sun is eno mously larger than the moon. A explanation is found in Figure 20 The observer on the earth, of cours has no way of judging astronomic distances visually. Thus, the larg bundle or cone of light rays fro the sun, S, converge, and at S^1, th angular size is very nearly th same as the angular size of the moo

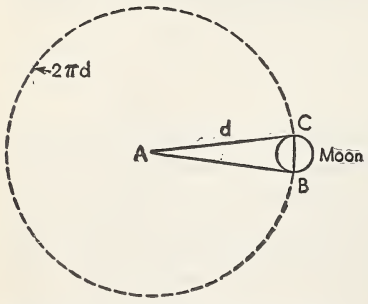


FIGURE 208. APPROXIMATE RELATION BETWEEN ANGULAR DIAMETER AND DISTANCE

To translate angular size into miles of diameter is a simple application of geometry. (Refer to Figure 208.) For a very small angle, the arc made by that angle can be considered equal to the chord. By the same reasoning, the line BC in Figure 208 can be considered the diameter of the moon. If d is the mean distance of the moon to the earth, then the mean path of the moon is given by $2\pi d$. For an angle of one degree of arc:

$$CB = \frac{2\pi d}{360°};$$

or an angle of one minute of arc:

$$CB = \frac{2\pi d}{360 \times 60} = \frac{d}{3438}.$$

Since the mean distance of the moon from the earth is 238,900 miles, and its angular diameter is about thirty-one minutes of arc, its mean diameter will be:

$$\frac{238{,}900}{3438} \times 31 = 2160 \text{ miles.}$$

The diameter of the moon is thus shown to be slightly more than one-fourth that of the earth. It is, in fact, one of the largest of the satellites, being exceeded by some of the satellites of Jupiter and Saturn.

In Chapter 15, it was shown that, with respect to the stars, the moon makes its complete orbit every twenty-seven and one-third days. From this, the average velocity of the moon in its orbit can be calculated to be about 2290 miles per hour or a little over 0.60 mile per second.

The distance and size of the moon, which is the earth's nearest celestial body, can be determined by the methods of trigonometry. Similar attempts to determine the distance and the size of the sun yielded widely differing results. The difficulty, for a long time unsuspected, really lay in the enormously greater distance to the sun. This problem was not successfully solved until about a hundred years ago, a fact in itself an indication of its intrinsic difficulty. The solution lay in the perfection of a new method of measuring interstellar space, the *method of parallax.*

The Method of Parallax

The parallax of the sun or of a star is the result of an apparent motion of that body with reference to a background of stars, because of a change in the position of the observer. This is a phenomenon with which everyone is familiar, though it is not always labeled parallax. For example, hold a pencil in a vertical position about twelve inches in front of the eyes. (Refer to Figure 209.) Then observe its position relative to the wall in the background, first with the left eye closed, then with the right eye closed. The pencil will seem to change its position with respect to the background. Actually, of course, the pencil has been stationary. Exactly the same phe-

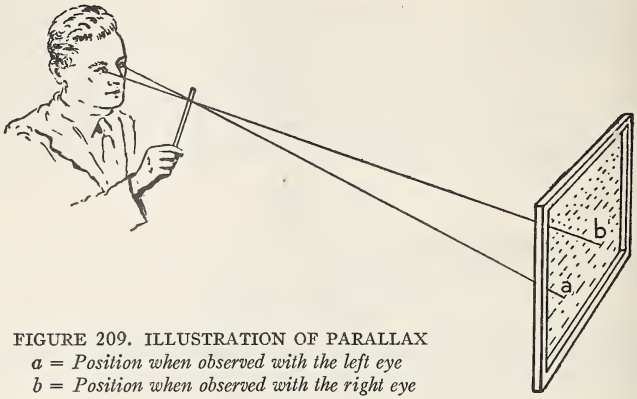


FIGURE 209. ILLUSTRATION OF PARALLAX
a = *Position when observed with the left eye*
b = *Position when observed with the right eye*

nomenon occurs when the position of a star is located with respect to th only possible background, the field of stars beyond the star being observed Refer to Figure 27 in Chapter 5. When the earth is in position A, the sta S_1 is apparently much closer to star S_2 than it is to S_3; six months later, th earth is in position B, and S_1 is now apparently nearer the star S_3. This ap parent motion results in an angle AS_1B. The astronomer arbitrarily refer to half of this angle as the star's parallax.

The astronomer makes use of two kinds of parallax, *geocentric* an *heliocentric*. (Figures 210 and 211.) In Figure 209, the base line for th angle of parallax is the distance between the eyes. For bodies in space no too far from the earth, the base line for making observations is the earth radius. This means, of course, that observations will be separated by a interval of about twelve hours. The geocentric parallax, then, is the angl made by a celestial body and the earth's radius. For stars, the angle o geocentric parallax becomes so small that measurement is impossible. Th angle of parallax can be made larger by extending the base. The onl larger base line possible is the radius of the earth's orbit, one astronomica unit (Figure 211). An interval of about six months must elapse betwee the observation of a star when the earth is at E_1, and the observation of tha

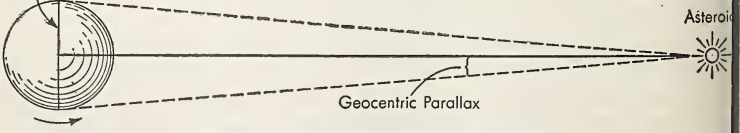


FIGURE 210. GEOCENTRIC PARALLAX

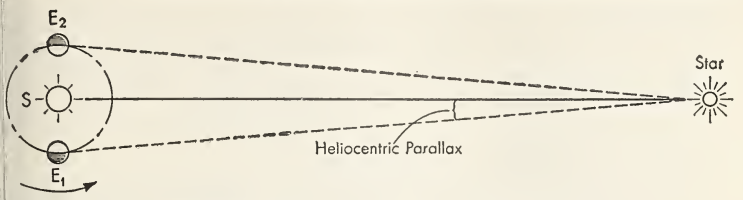


FIGURE 211. HELIOCENTRIC PARALLAX

ar when the earth is at E_2. The heliocentric parallax, then, is the angle ade by a star and the radius of the earth's orbit as a base line.

The angle of parallax, naturally, is a part of a triangle, which is very ongated. Furthermore, as the distance to a star increases, the angle of arallax must decrease in an inverse ratio to the real distance of the star. his means that approximately,

$$d_1 : d_2 = x_2 : x_1,$$
$$d_2 x_2 = d_1 x_1.$$

rom this statement there is derived the very important relationship

$$d_2 = \frac{d_1 x_1}{x_2},$$

$$\text{Distance to far star} = \frac{\text{Distance to near star} \times \text{Parallax near star}}{\text{Parallax far star}}$$

he importance of this conclusion is that it is the basis for the method first ed to give a reliable conception of astronomical distances and of the size of e universe. This is the parallax method for finding astronomical dis- nces.

From an algebraic point of view, the relationship

$$d_2 = \frac{d_1 x_1}{x_2}$$

ntains four quantities, which means that three of these quantities must be own to solve for the fourth quantity d_2. In other words, it is necessary

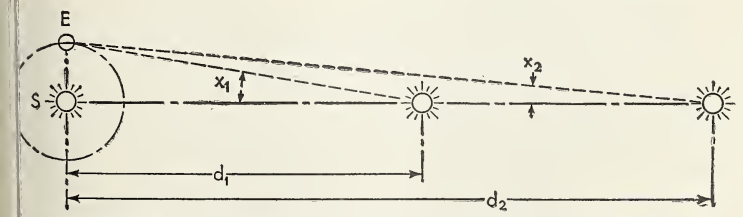


FIGURE 212. STELLAR PARALLAX VARIES WITH DISTANCE

to know the distance and parallax of some heavenly reference body, such a the moon or an asteroid. These data concerning the moon are as follows

Moon's mean geocentric parallax = x_1 = 57 min 3 sec, or 3423 sec of arc.
Distance to the moon = d_1 = 238,000 miles.

The Distance to the Sun

In our growing picture of the universe, an exceedingly important quantit is the mean distance from the earth to the sun. This is the basic unit whic is used to measure the size of the universe, and is a quantity that nearl every person has taken on faith since he memorized it in grammar schoo It is very nearly ninety-three million miles, or nearly four hundred time greater than the distance to the moon. Aristarchus made a calculation o the distance to the sun and had difficulty in getting his contemporaries t believe that the sun's distance was at least twenty times greater than tha to the moon. The problem of the distance to the sun was not solved unt the nineteenth century for two reasons: (1) the inability of man to conceiv of such large distances; and (2) the impossibility of solving the proble until telescope mountings had been perfected to measure relatively sma angles of parallax. The heliocentric parallax of the nearest fixed sta Proxima Centauri, for example, is only 0.78 seconds of arc.

Knowledge of the actual distance to the sun represents an achievement o modern astronomy and is based upon a precise knowledge of the sun parallax, making use of the relationship

$$d_2 = \frac{d_1 x_1}{x_2}.$$

The solar parallax with respect to the earth, x_2, has been taken to be 8.8 seconds of arc. Using the data pertaining to the moon before given, w have:

$$\text{Mean distance to sun} = d_2 = \frac{d_1 x_1}{x_2}$$
$$= \frac{(238900 \text{ miles})\ (3423 \text{ sec})}{(8.80 \text{ sec})}$$
$$= 92{,}900{,}000$$

The parallax is the angle subtended by the earth's radius and the center o the moon. The face of the moon is a relatively large surface in the sk hence, it is very difficult to make observations of its precise center. It is im possible to measure the moon's parallax and distance with great precision b this method. Because of this, the astronomer prefers to use data pertai ing to some other heavenly body, usually the planetoid Eros. Althoug this tiny planetoid is only fifteen miles in diameter and appears as a speck i the field of view of a telescope, at times it has approached the earth as clo as 13,840,000 miles. As a consequence, its angle of parallax can be mea

red with much greater precision than that of the moon. Furthermore, ros comes close enough to the earth to permit its distance to be determined ith a high degree of accuracy by the methods of trigonometry.

The parallax of Eros, in a certain observation, was found to be 59.07 seconds, and the distance 13,840,000 miles; hence, the astronomical unit

$$= d_2 = \frac{d_1 x_1}{x_2} = \frac{59.07 \times 13{,}840{,}000}{8.80} = 92{,}870{,}000 \text{ miles.}$$

his, the present accepted value for the mean distance from the earth to the n, is the usual unit used to express astronomical distance. Thus, the disnce of Neptune is 30.07 astronomical units.

The Size of the Sun. Modern science has today supplied the answer to e ancient question about the size of the sun, from its mean angular dimeter 31 minutes 59 seconds of arc. Using the known distance to the sun d the relationship given on page 323,

$$\text{Mean diameter of sun} = \frac{92{,}870{,}000 \text{ mi} \times 31\ 59/60 \text{ min}}{3438 \text{ min}}$$
$$= 864{,}000 \text{ miles}$$

his proves that the diameter of the sun is over a hundred times greater an that of the earth. But as a star, our sun is noteworthy only because it so close to the earth. The star Aldebaran has a diameter forty times that our sun. Betelgeuse is three hundred times larger, while Antares is so rge that over four hundred of our suns could be laid edge to edge along its ameter. Antares would fill our solar system almost to the planet Jupiter.

stronomical Space

"The heavens declare the glory of God; and the firmament showeth His ndiwork," sang the Psalmist, revealing the prevalent conception of the niverse in his time. It consisted of seven great bodies, the moon, Venus, ercury, the sun, Mars, Jupiter, and Saturn, rotating in space around the rth. Out beyond Saturn was the firmament, upon which was fastened e fixed stars. The concept of the firmament resembled that of a vast here in space, the celestial sphere, an idea still persisting, even though we ow that such a celestial surface does not exist. No one can observe the ars on a clear night and not be impressed by their number. It is easy to t the impression that outer space is crowded with celestial objects. But r impression is due to our own inability to conceive of the distances inlved in astronomical space. Actually, astronomical space is mostly pty. The star closest to the earth, Proxima Centauri, is 4.2 light-years 25×10^{12} miles away from the earth. After years of searching with highwer telescopes, astronomers have found only ten stars within eleven lightars of the earth. This indicates that our entire solar system must indeed a tiny speck in a vast universe of nearly empty space.

Man's undiscourageable search for the truth is symbolized by his con-

tinuing effort to plumb the depths of outer space. He has found it neces sary to devise and use astronomical measuring sticks of ever-increasin length. Each of these measurements in space was in itself a notabl achievement. These steps were as follows:

(1) The measurement of the mean radius of earth: 3958.82 miles
(2) The measurement of the mean distance to the moon: 239,000 miles
(3) The measurement of the mean distance to the sun — the astronomic unit: 92,870,000 miles
(4) The measurement of the distance to the nearest star, Proxima Centaur 4.2 light-years with a parallax of 0.785 seconds.

Light travels 186,000 miles per second, and since there are 31,560,00 seconds in a year, it follows that

$$\begin{aligned} 1 \text{ light-year} &= 31{,}560{,}000 \times 186{,}000 \text{ miles} \\ &= 5.88 \times 10^{12}, \text{ or nearly} \\ &= 6 \text{ million million miles, or} \\ &= 63{,}300 \text{ astronomical units.} \end{aligned}$$

For plumbing the outer reaches of astronomical space, a larger unit, th *parsec*, has been invented. This is the distance that will give a star parallax of one second. The definition is responsible for the term — *pa* allax *sec*-ond. It is a simple calculation to translate the parsec into the fo lowing units:

$$\begin{aligned} 1 \text{ parsec} &= 1 \text{ second of parallax (heliocentric)} \\ &= 3.26 \text{ light-years} \\ &= 206{,}263 \text{ astronomical units} \\ &= 2 \times 10^{13} \text{ miles} \end{aligned}$$

Experimentally it is not possible with the best of modern telescopes measure trigonometric parallaxes smaller than 0.01 second. This aut matically sets a limit of slightly over three hundred light-years for th measurement of star distances by the method of trigonometric parallax.

The Brightness of Stars

An obvious method of classifying stars is on the basis of their appare brightness. In order to place these measurements on an objective basis, is necessary to recognize clearly that the apparent brightness of a star — i star magnitude — depends upon two factors, its intrinsic or absolu brightness, and its distance. The apparent brightness increases with increase in absolute brightness, being directly proportional, but decreas with an increase in distance.

Inverse Square Law for Light Intensity

Light from a point source spreads out evenly in all directions. For given light source, the intensity can be considered the amount of light d tributed over one unit of area on the inside of a sphere of radius d, or

$$I(\text{ntensity}) = \frac{B(\text{rightness})}{\text{Area of sphere}} = \frac{B}{4\pi d^2}.$$

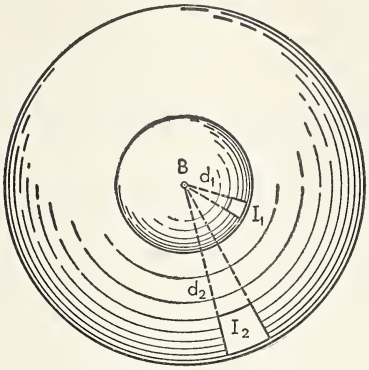


FIGURE 213. EFFECT OF DISTANCE ON INTENSITY OF LIGHT FROM A SOURCE

With an increase in distance from the source, the light is distributed over a larger and larger area. For example, in Figure 213, what is the relation between the two light intensities, I_1 and I_2? Applying the relationship given above,

$$\frac{I_2}{I_1} = \frac{\dfrac{B}{4\pi (d_2)^2}}{\dfrac{B}{4\pi (d_1)^2}} = \frac{4B}{\pi (d_2)^2} \times \frac{\pi (d_1)^2}{4B} = \frac{(d_1)^2}{(d_2)^2}.$$

That is, the intensity of light from a given light source varies inversely as the distance squared. If light at a distance of ten feet has a certain intensity, at a distance of one hundred feet, it will have an intensity one one-hundredth as much, since

$$\frac{I_2}{I_1} = \frac{(d_1)^2}{(d_2)^2} = \left(\frac{1}{10}\right)^2 = \frac{1}{100}, \text{ or } I_2 = \frac{1}{100} I_1.$$

This is usually referred to as the Inverse Square Law for light. It is analogous in its form to the Inverse Square Law for gravitational attraction; where

$$F \propto \frac{1}{d^2}.$$

Star Magnitudes

The apparent brightness of stars is expressed in terms of star magnitudes, a numerical scale which increases as the apparent brightness decreases. The average brightness of the twenty brightest stars is taken as a standard, as magnitude one. Stars of the first magnitude are one hundred times brighter than stars of the sixth magnitude, which are just visible to the

naked eye. Numerically, one hundred is very nearly $(2.51)^5$. Hence a change of five magnitudes corresponds to a change of $(2.51)^5$, or one hundred times in apparent brightness. A change of one magnitude means a 2.51 fold decrease in brightness. On this scale stars brighter than first magnitude stars have magnitudes less than one, or are negative. These facts may be summarized in table form:

Table 22. Relative Brightness and Star Magnitudes

Star magnitude	− 2	− 1	0	1	2	3	....	6
Brightness in terms of first magnitude star	$(2.51)^3$	$(2.51)^2$	(2.51)	1	$\frac{1}{2.51}$	$\frac{1}{(2.51)^2}$	....	$\frac{1}{(2.51)^5}$
	16	6.3	2.5	1	$\frac{1}{2.5}$	$\frac{1}{6.3}$	....	$\frac{1}{100}$

Examination of Table 22 reveals that a difference of one star magnitude means a change in brightness of 2.5 times, a change of two magnitudes means a change in brightness of $(2.5)^2$ or 6.30 times. (Refer to Table 23.)

Table 23
Change in Star Brightness in Terms of Magnitude Difference

Magnitude difference	1	2	3	4	5	10
Change in brightness	2.51	$(2.51)^2$	$(2.51)^3$	$(2.51)^4$	$(2.51)^5$	$(2.51)^{10}$
		6.3	16	40	100	10,000

Polaris and the brighter stars in Ursa Major — the Big Dipper — are second magnitude stars. The remaining stars in Ursa Major belong to the third magnitude. Sirius, the most conspicuous star in the southeastern sky in winter, has a magnitude of − 1.6. The brightness of Venus is variable, but is usually about − 4. The full moon and the sun have magnitudes of − 11.2 and − 26.7 respectively. In order to make a comparison of the brightness of the sun and the full moon, determine the difference in magnitude, which is about 15. (Refer to Table 23.) It indicates that a magnitude difference of 5 corresponds to a change in brightness of 100. Hence the sun is $(100)^3$, or a million times brighter than the full moon.

Absolute Magnitudes

It is difficult or impossible to measure the intrinsic brightness of a star. Instead, the astronomer compares the brightness of stars by comparing their magnitudes at a standard distance, ten parsecs, where the parallax would be 0.10 second. This corresponds to a distance of 32.6 light-years. This reference magnitude is called the *absolute magnitude*. It can be defined as the brightness that all stars would have if they were all at a uni

rm distance of 32.6 light-years from the earth, a distance corresponding a parallax of 0.10 second.

e Leavitt-Shapley Law

Astronomers estimate that six thousand stars can be seen with the naked e and about seventy million with the largest telescopes. An inkling of e vastness of outer space comes with the realization that most of these ars are more than three hundred light-years from the earth. The ques- on, How far?, has again been answered by the astronomer during this ntury, through the study of a class of pulsating stars called *Cepheid riables*. They were so named for the first star of this type to be studied. ese Cepheid variables, as stars, are super-giants with masses from ten fifty times that of our sun. Their diameters vary from 5,000,000 to 0,000,000 miles, and in intrinsic brightness they exceed our sun from o hundred and fifty to ten thousand times. They are unique, however, that they vary in brightness in a regular manner. Thus, the namesake these variables, Delta Cephei, varies regularly from maximum to mini- um to maximum brightness every five days and ten hours. This inter- l is called its period. Furthermore, study of large numbers of these riables revealed that the actual luminosity varied in a regular manner th the period, and that the longer the period, the greater the absolute an magnitude of the star. The relationship between these two quantities shown in Figure 214. Thus, a Cepheid variable star, whose period of

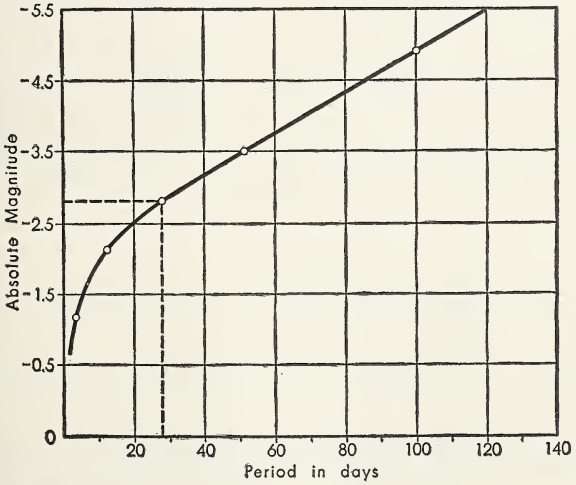


FIGURE 214. RELATION BETWEEN ABSOLUTE MAGNITUDE AND PERIOD IN CEPHEID VARIABLE STARS

(*After Shapley*)

fluctuation from maximum brightness to maximum brightness is thirty days, would have an absolute mean magnitude of -2.8. The credit for this relationship belongs to Miss Leavitt of the Harvard Observatory, and to Harlow Shapley, director of the same observatory, and is called the Leavitt-Shapley Law.

The importance of this relationship lies in the fact that it can be used to measure the depths of outer astronomical space by determining merely the (1) apparent brightness (star magnitude) and (2) the period of a Cepheid variable. From the period and the Leavitt-Shapley Law (Figure 214), the absolute magnitude can be determined. Knowing, then, the absolute and apparent magnitudes, it is a simple calculation to determine the distance to the variable by applying the Inverse Square Law for light.

This method of measuring astronomical distances is the most powerful method now in the hands of the astronomer. In the northern sky Cassiopeia, a very conspicuous constellation shaped like the letter W, may be seen about thirty degrees below Polaris. About twenty degrees below Cassiopeia can be seen a faint patch of light, which powerful telescopes reveal as a huge spiral of luminous material, called a *spiral nebula*. Within this patch of light can be found Cepheid variables whose periods and apparent brightness indicate that they are at the gigantic distances of 270,000 parsecs or 870,000 light-years. This corresponds to a distance of 5.4×10^{18} miles! And there are stars beyond them!

How far does the universe reach? The Rockefeller Foundation has donated six million dollars to build a telescope with a mirror lens 200 inches in diameter. This telescope, the mirror of which is twice as large as any that has been constructed up to this time, is to be housed in an observatory on Mount Palomar in Southern California. It will penetrate four times farther into space than has been possible up to this time. A momentous question: What will this new telescope reveal concerning space beyond a million light-years? Surely science has come a long way from the concept of the Psalmist of the Old Testament!

SUMMARY

1. The distance to the moon, sun, and stars is measured in terms of the mean distance of the earth.
2. The distances to the moon and certain asteroids which come comparatively close to the earth are measured by trigonometrical methods.
3. The diameter of the moon and sun can be calculated from their apparent angular size after their distances from the earth are known. The diameter of the moon is slightly more (8%) than one-fourth of the diameter of the earth.
4. The method of parallax is used to measure the distance to the sun and the nearer stars — those within three hundred light-years of the earth

$$\text{Distance to far star} = \frac{(\text{Distance to near star})\ (\text{Parallax near star})}{\text{Parallax far star}},$$

$$d_2 = \frac{d_1 x_1}{x_2}.$$

The parallax of a star is the result of its apparent motion with reference to a background of stars, resulting from a change in the position of the observer. The geocentric parallax of a celestial body is the angle made by the body and the earth's radius. The heliocentric parallax is the angle made by a celestial body and the radius of the earth's orbit.

The distance and parallax of Eros have been used to measure the mean distance to the sun from the observed parallax of the sun.

The mean distance from the earth to the sun, 92,870,000 miles, is taken as the astronomical unit for discussing the size of the solar system.

The *light-year* is a distance unit for astronomical space. It is the distance traversed by light in one year. It is equal to 5.88×10^{12} miles or 63,300 astronomical units.

The *parsec* is the unit used to measure the distance to stars and the outer depths of astronomical space. The parsec is the distance corresponding to one degree of parallax, or 3.26 light-years, or 206,263 astronomical units.

The intensity of light from a given source varies inversely as the square of the distance.

The apparent brightness of a star depends upon its intrinsic brightness and its distance.

The apparent brightness of a star is expressed in star magnitudes. Stars of sixth magnitude are barely visible to the naked eye and are one one-hundredth $(1/(2.51)^5)$ as bright as first magnitude stars. A change of one magnitude means a 2.51-fold change in apparent brightness. Star magnitudes increase as apparent brightness decreases.

The absolute magnitude of a star is its magnitude computed for a distance of ten parsecs of a parallax of 0.10 second. Absolute magnitudes are used to compare the relative brightness of stars.

Cepheid variable stars pulsate in volume and temperature in a regular manner. As a result, they change from maximum to minimum to maximum brightness in a regular manner. The time for this change is called the period.

The Leavitt-Shapley Law gives the relation between the absolute mean magnitude of a Cepheid variable star and its period.

The distance to Cepheid variables can be computed from their apparent brightness and period by utilizing the Leavitt-Shapley Law and the Inverse Square Law for light.

Observations upon Cepheid variable stars are of importance because of the information they give concerning the distance to stars which are so far away that the trigonometrical parallax cannot be measured.

STUDY EXERCISES

1. Explain why the accuracy of the measurement of the distance to the moo the sun or any other astronomical body must depend on the precision po sible in the determination of the radius of the earth. (Refer to Figure 20 With what precision is the radius of the earth known?
2. Mars approaches the earth at times as close as 35,000,000 miles. If its ang lar diameter at the time is twenty-five seconds, what is its diameter in mile
3. If x_1 and x_2 represent the parallaxes of two stars at distances d_1 and respectively, which of the following expressions correctly indicates the relati that exists between the parallax and the distance?

$$(a)\ \frac{d_1}{d_2} = \frac{x_1}{x_2} \qquad (b)\ \frac{d_1}{d_2} = \frac{x_2}{x_1}$$

$$(c)\ d_1x_1 = d_2x_2 \qquad (d)\ d_2 = \frac{d_1x_1}{x_2}$$

$$(e)\ d_2 = \frac{d_1x_2}{x_1}$$

4. The parallax of the star Proxima Centauri is 0.78 second, and its distar from the earth is 4.2 light-years. How far from the earth is the star Cordo which has a parallax of 0.26 second?
5. The parallax of Sirius is 0.37 second. What is its distance in miles and lig years? In making this calculation use the parallax and distance data Proxima Centauri given in the preceding problem. Sirius is the bright star in the southeastern sky.
6. Are the parallaxes of the nearer stars heliocentric or geocentric? Explai
7. If the heliocentric parallax of a star is so small that it cannot be relia measured, will there be any observable annual apparent motion (parallac displacement) of that star with respect to stars behind it? Explain.
8. (*a*) About 30° beyond the end of the handle of the Great Dipper, U Major, is a very conspicuous star, Arcturus. Its parallax is 0.088 s ond. Its star magnitude is 0. What is its distance in (1) parse (2) light-years, and (3) astronomical units?
   (*b*) How many times brighter is Arcturus than Polaris, whose star magnitu is 2?

   Answers: (a) 11.4 parsecs; (a) 37 light-years; (a) 2.37×10^6 (b) 6.30 times brighter
9. What is the absolute mean magnitude of a Cepheid variable star with a per of eighty days?

FOR FURTHER READING

1. JEANS, JAMES H., *The Universe Around Us.* 3d edition; New York: T Macmillan Company, 1934.

   Very readable. Parts of Chapter I, such as pages 15–39 and 61–82, treat question of the size of the universe.

BARTKY, W., *Highlights of Astronomy.*

Chapter 7 is concerned with the sidereal universe and such topics as parallax of stars, star magnitudes, and Cepheid variables. See also the note on Eros on page 205.

WHIPPLE, F. L., *Earth, Moon and Planets.*

The author, an outstanding astronomer of Harvard Observatory, is very successful in bringing the human element into his presentation of astronomy. This small volume is about the solar system for the general reader. The significance of star parallax and Eros is discussed on pages 45–49.

18

The Sun — The Cause of Change

THE SUN is our nearest star; it is by all odds the astronomical body of great est importance. This was even more true for primitive man than fo modern man, since he had to depend upon the sun for warmth. He kne how to build fires to warm his cave home and to cook his food, but th problem of fuel was not always an easy one to solve. The first civilizatio developed in regions comparatively close to the equator. Early man kne from experience that the more vertical rays of the sun, in regions like Bab lonia and Egypt, meant greater warmth, longer days, and longer growi seasons. Because of this dependence many early peoples considered th sun a deity. In the ancient religion of Egypt, the chief deity was Ra, th sun-god, represented by a lion wearing the solar disk. The banishment magic and superstition by modern science has hardly lessened our feeli of dependence upon the sun. On the contrary, science has increas enormously our knowledge of the many ways in which we are depende upon that heavenly body. The sun is the dictator of the solar system, co trolling the motions of the earth, the planets, the comets, and the myri of meteors traveling through the solar system. The magnitude of t gravitational pull of the sun will be discussed later in this chapter.

The sun is a star. At night we can look above us and see literally tho sands of stars. We call them *fixed stars* because they maintain positio in relation to each other in the sky, positions which do not change app ciably with time. Most of these stars appear as twinkling points of lig Sirius, for example, is often visible in the southeastern sky. It is easy find because, with the exception of Venus, it is the brightest object in t sky. It appears to the eye as a single star. Yet Sirius is really a double st or *binary*, a system of two stars revolving one about the other. Th combined mass is 3.4 times that of the sun. Our solar system is a hu vortex of moving parts, with the sun as the center, but if you could sudde transfer yourself out into the celestial space of the Milky Way, you wo have difficulty in finding our sun as a star. As a member of the univer the sun is a very ordinary star, similar to millions of others in size, temp ature, and composition. For man, however, it is the most important s

cause it is almost the entire source of warmth, power, and light upon the rface of the earth. Some heat reaches the earth from stars, some results)m radioactive changes deep in the earth, and some from the forces of mpression on the earth's interior. But the amount of this heat is insig- icant when compared with the heat that is continually streaming to the rth from the sun. Our knowledge of the sun is much more complete an that of any other star, because it is our nearest stellar neighbor, and erefore easier to study. The next nearest star, Proxima Centauri, is 5,000 times farther from the earth than the sun.

me Facts About the Sun

Our best standard of comparison in discussing the sun is the earth and e solar system itself. The law of universal gravitation can be used to ermine that the mass of the sun is 332,000 times that of the earth, and out 700 times the combined mass of all the planets. As shown in the ceding chapter, the diameter of the sun is 108 times greater than that the earth, and its volume is very nearly 1,300,000 times greater. It is big, in fact, that it is about 600 times larger in volume than all the nets combined. The entire earth-moon system could easily be lost hin the sun.

So far the emphasis has been upon the enormous size of the sun. But sun, as has been stated before, is a very average star. There are other as known in space beside which our own would be a mere speck in the r. Betelgeuse, for example, is so large that it would fill our solar system as far as the orbit of Mars; and Antares has a volume more than 000,000 times greater than that of our sun.

Light is emitted only from the surface of the sun. A photograph of sun gives the impression of a sharp transition surface between the itself and outer space. (Refer to Figures 216 and 217.) However, s is only an illusion. The outer surface of the sun is made up of four tinct layer-like spheres outside the invisible portion of the sun — the *tosphere*, *reversing layer*, *chromosphere*, and *corona*, and in that order n inner to outer layer. These layers, exclusive of the corona, are ut a thousand miles in depth. Therefore, it is incorrect to speak of surface of the sun. The apparent surface is the photosphere, which is light-emitting portion of the sun. Light from below a certain level er leaves the sun. It is absorbed by the material in the sun itself much

Table 24. Résumé of Important Data about the Sun

Distance	92,870,000 miles
Diameter	864,000 miles
Mass	332,000 that of the earth
Surface gravity	27.6 that of the earth
Mean density	1.4 g/cc (water = 1 g/cc)
Surface temperature	6000° C.
Central temperature	40×10^6 C. (?)
Rotation	25–34 days

as light is absorbed by the water near the surface of a lake — darkness pr vails at the bottom of all deep bodies of water. Nearly all the light emitte by the sun comes from a layer just above the zone of total absorptio This is the photosphere. Since it is comparatively thin, about one hundr miles, it acts as a luminous surface. The vast disturbances responsible f sun spots and prominences which are discussed below, occur in the phot sphere. It is this surface which has a temperature of about 6000° C. Th light from the photosphere is "white" and exceedingly intense. Metho for measuring the temperature of the sun will be discussed in Chapter 4 Permanent blindness can result from looking directly at the sun with t naked eye; an overexposed photographic film or piece of smoked gla should be used. A still better method is to focus the image of the sun on white surface by means of a small telescope.

The reversing layer, three thousand miles in thickness, is invisible, a of interest only to professional astronomers. The upper atmosphere of t sun, many thousands of miles in thickness, has a rosy tint, which is respo sible for its name — the chromosphere, or color sphere. It is compos principally of hydrogen and helium.

Outside the chromosphere is the corona. Its density is exceedingly lo This can be inferred from the fact that comets have been observed to pa through the corona without meeting enough resistance to cause a notic able retardation. The light emitted by the corona is so faint that it can observed only when the light of the photosphere is blotted by the mo

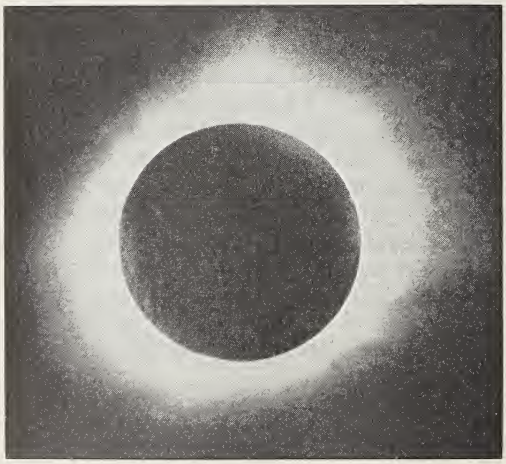


FIGURE 215. CORONA OF SUN AT TIME OF TOTAL ECLIPSE OF JANUARY 24, 1925
(*Courtesy of Yerkes Observatory*)

ıring a total eclipse. (Refer to Figure 215.) For this reason the total ne in which the corona has been under observation with modern instru- ents is less than an hour. It is not surprising that astronomers know ry little about the nature of the corona.

Photographs of the sun reveal an almost perfect disk, like that of the on. But here the similarity ceases, for the sun is far from being a iescent body. Violent storms on the surface of the sun result in *sun ots*, visible from the earth. Some of these sun spots are hundreds or ousands of miles in diameter. While the surface temperature of the sun believed to be about 6000° C., estimates for the temperature of the ıter run as high as 40,000,000°. Such temperature precludes the pos- ility of solid matter in the sun. Photographs of the sun's edge (Figure 5) reveal the magnitude of the storms on the sun by showing *eruptive ominences* of ejected matter which often rise to a height of two hundred ousand miles in the course of two or three hours. This means that the cted matter leaves the sun's surface with velocities as high as one hun- ed to two hundred miles per second.

Most of this material eventually returns to the sun because of the great raction exerted by gravitation on the sun's surface, a gravitational pull

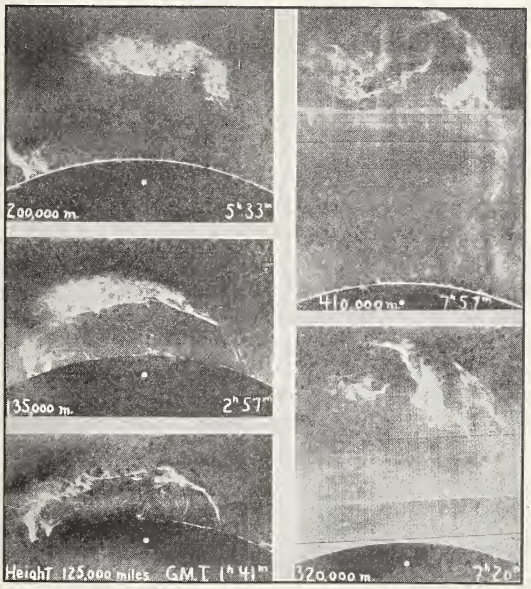


FIGURE 216. EXTRAORDINARY PROMINENCE ON SUN, MAY 29, 1919
(*Courtesy of Yerkes Observatory*)

nearly twenty-eight times greater than that on the surface of the eart
The *critical velocity* of escape on the earth is about seven miles per secon
This means that a ball thrown from the earth with a velocity greater th
seven miles per second would leave the earth forever. On the sun, t
escape velocity is about 383 miles per second, a value so high that it
possible only for extremely light particles, such as electrons, to stream o
into space. It is these electrons which occasionally reach the earth
atmosphere in large numbers to produce the aurora borealis and to pl
havoc with all forms of electrical communication.

Sun Spots

Until the perfection of the telescope by Galileo, man's knowledge of t
sun did not go much beyond that possessed by the ancients. Galil

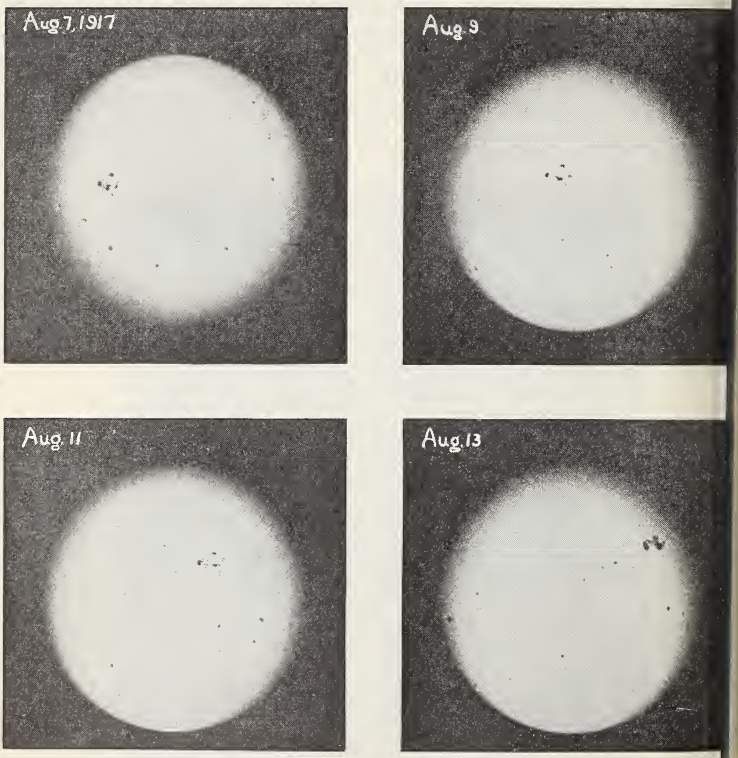


FIGURE 217. ROTATION OF THE SUN SHOWN BY SUN SPOTS
(*Photographs of sun's disk taken August 7, 9, 11, and 13, 1917. Courtesy of Yerkes Observatory.*)

bserved, for example, the gradual movement of the sun spots across the ce of the sun and concluded that the sun rotates on its axis, a conclusion at has been confirmed since that time. The sun is a body of relatively w density, being largely gaseous. This accounts for a peculiarity in its tation: it rotates faster at its equator than it does near its poles. The riod of rotation at its equator is about 24.7 days, while in the region near s poles the period is as much as thirty-four days. This fact is, of course, ditional evidence that the sun cannot be a solid body. The direction of tation of the sun is the same as that of the earth — from west to east.

Long observation of sun spots has shown that the frequency of their pearance varies over a period of about eleven years. In 1912 there were ry few sun spots, and this was true again in 1923 and 1933. The years 17 and 1928, however, were marked by great sun-spot activity. This nclusion is based on many facts; but the reason for this periodicity is one the questions to which modern science has not yet found a satisfactory swer. There is no doubt that sun spots affect our earth. For instance, period of sun-spot activity is always accompanied by great displays of e aurora borealis and by magnetic storms, often severe enough to render eless not only the radio, but also our telephone and telegraph lines of mmunication. There is also reason to believe that our weather is in-ienced by the sun-spot cycle, but this is another relationship that still vaits further study.

e Sun is the Dictator of the Solar System

In Chapter 14 the force of gravitation was discussed. The force of at-action between two bodies of small mass is insignificant, but the mass of e earth, together with the much greater mass of the sun, results in a utual force which is enormous. Newton's Law of Universal Gravitation ows that the force would be sufficient to break a steel cable nearly three ousand miles in diameter. It is this force that keeps the earth traveling an elliptical path instead of a straight line. Newton was the first to pothesize the existence of such an enormous force between the sun and e earth. He could not picture any process by which it could act through arly empty space. Modern science is still unable to explain *how* this rce acts. The sun is responsible for similar forces between it and the rious members of the solar system. These forces hold our solar system gether and largely control its various motions.

e Sun as the Primary Source of Life

We have mentioned the importance of the sun as the source of warmth, wer, and life upon the surface of the earth. Fundamentally, the sun is e agent of all change on the earth which involves the atmosphere. In apter 8 we studied the geological process called gradation, which results the wearing-down of the earth's crust by weathering, the action of

running water, ground water, the wind, glaciers, and the like. All the processes are possible only on a planet blessed with an atmosphere a continuously bathed in light from the sun. By the remarkable process *photosynthesis*, plants manufacture sugars, starch, and cellulose from carb dioxide, water, and a few minerals taken from the soil. Coal, our m important fuel, represents an accumulation and modification of plant su stance which grew many geological ages ago. When coal is burned in furnace, heat is utilized which came originally from the sun. The c culation of the atmosphere, resulting in what we call weather, is due the unequal rates of heating and cooling of large land and water mass The continuous maintenance of moisture in the air which makes ra streams, and waterfalls, is possible because of the sun. Electricity g erated by the rush of water through a turbine represents a small porti of the sun transported to our earth and thence into our homes.

To appreciate the truth of the statement that the sun is the agent of change, just consider what would happen to the earth if by some ca strophic event the sun should suddenly cease to shine. The earth, of cour would be plunged into darkness, and in a very short time it would be deed a changeless world. Plant life would cease, the various streams t world over would be emptied into the oceans where all the water on t earth would accumulate and eventually freeze solid. The earth's atm phere would cease to circulate, and in time all forms of plant and anim life would die. Life is not possible in a changeless world.

The Concept of Energy

So far we have been referring to a certain something that exists in t sun and which is continuously streaming earthward, making life an myriad changes possible. This mystical something, the nature of whi no one yet fully understands, we call *energy*. Let us introduce this to by describing an experiment that illustrates how simple and yet how di cult it is to understand the concept of energy. In Figure 218 is a doub convex lens, which may be made of glass or even of ordinary ice. This used to bring the parallel sun rays a focus on a piece of black cloth. Ev on a cold winter day, it would be o a matter of minutes before the piece cloth would burst into flame. Duri this process, there is no change in t condition of the lens. If an ice lens used, it has no tendency to melt as result of the passage of the sun's ra Even to a casual observer the flame re resents heat just like that which mak toast, operates a steam locomotive,

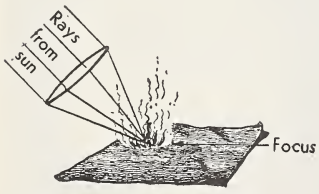


FIGURE 218
A LENS MADE OF ICE IGNITES A PIECE OF BLACK CLOTH
The ice is not melted

ats a house. Though there is no idence of heat as such where the sun's ys passed through the ice lens, it is vious that this heat has some con- ction with the rays that come from e sun.

Suppose this experiment is modified th nothing more complicated than ne pieces of iron, copper wire, and a y electric light bulb to show the esence of electrical energy. A num- r of iron wires are joined to a similar mber of copper wires in two pairs of junctions, labeled *A* and *B* Figure 219. Placed in the circuit is a small lamp socket with the electric ht bulb. The lens can now be used to focus the rays from the sun on e pairs of junctions labeled *A*. Immediately, the tiny electric bulb be- s to glow. This continues only while the sun's rays are actually fo- sed on the junction *A*. The emission of light by the bulb is possible cause of a flow of electricity, a form of energy.

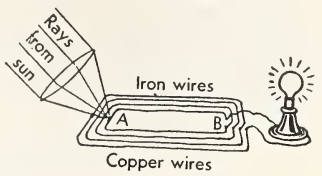


FIGURE 219
ELECTRICITY FROM SUNLIGHT
Sun rays focused on the junction of unlike metals result in an electric current to light the bulb.

The rate at which the earth receives energy from the sun is measured in ms of heat units received per minute per square centimeter of area. Cal- lations show that the heat received per square mile of land area is equiv- nt to the amount of heat needed to raise the temperature of seven hun- d and fifty tons of water from the freezing point to the boiling point in e minute! It is this energy that evaporates water from the oceans, rms the continents, causes weather, and produces vegetation. The en- y emitted per unit of area of the sun's surface is enormously greater, out seventy thousand horsepower per square yard. It is natural to raise e questions, "What is the source of this energy? What sort of power nt is the sun?" When thinking of the production of heat, we think of l and ordinary burning or combustion. Burning coal in a furnace liber- s heat, but, strange as it may seem, the sun is much too hot for coal or y other fuel to burn. The accepted explanation for the source of energy the sun is a story in itself, which will be discussed in Chapter 45.

Attention has been called to a number of isolated phenomena which have ne connection with light from the sun. We have referred to light, heat, ctricity, electric motors, and the motion of a train, with no attempt to lain the meaning of these terms. We shall find that a satisfactory ex- nation of these terms requires the understanding of one of the great fying concepts of science, the concept of energy. Thus far we have died a whole group of ideas associated with the concept of force, such as eleration and the laws of motion and momentum, which we owe to such rkers as Galileo and Newton. For nearly two hundred years the ideas ncerning force and momentum were often confused with the notion of

energy. The complete dissociation of the various confusing ideas concer ing force, momentum, and energy represents one of the great intellectu achievements of the nineteenth century. Energy, therefore, will be th subject of the next chapter.

SUMMARY

1. To us, the most important astronomical body is the sun, since (*a*) it contro our solar system, (*b*) it is our nearest star, and (*c*) it is by far the most impo tant source of energy for the earth.
2. Facts concerning the sun's mean distance, diameter, volume, mass, mea density, surface gravity, surface and interior temperatures, and rotation ha been determined.
3. Violent disturbances or storms on the sun result in eruptive prominences a sun spots.
4. The frequency of sun spots follows an eleven-year cycle. An explanation f the existence of the cycle is not known.
5. Without the sun, the earth would be a dead body devoid of all change a life.

STUDY EXERCISES

1. How can the astronomer be sure that the sun actually rotates? What is period of rotation? What is unusual about this rotation? How can this accounted for?
2. Describe the series of changes that would occur on the earth if, by so catastrophic event, the sun should suddenly cease to shine.
3. How long does it take for light to reach the earth from the sun?
4. One half of the earth is always illuminated, and the earth turns on its axis a uniform manner. Why, then, do the days vary in length and why do have seasons?
5. In what way would conditions on the earth change if the earth's axis shou suddenly shift until it was perpendicular to the ecliptic? Explain.
6. In what way would conditions on the earth change if the axis of the ea should suddenly shift until it was parallel to the ecliptic? Explain.
7. As an astronomical body, how should the sun be classified? How does compare with other members of its class?
8. At the right appear certain terms often used in discussing the sun. Associa these terms by number with the definitions given below.

.... Mean distance of sun from earth.
.... Position of earth at maximum distance from sun.
.... A planet has the following relative position: sun-planet-earth.
.... Passage of moon across sun's disk.

1. Corona
2. Total eclipse of su
3. True local noon
4. Aphelion
5. Perihelion

. Apparent path of sun's center among the stars.
. Actual path of earth's center among the stars.
. Time when sun is on the meridian.
. Minimum velocity for gaseous molecules to escape gravitational attraction.
. Halo of light extending many miles beyond the surface of the sun but visible only at times of total eclipse.
. The reddish outer layer of the sun.
6. Inferior conjunction
7. Astronomical unit
8. Chromosphere
9. Escape velocity
10. Ecliptic

FOR FURTHER READING

. Bartky, W., *Highlights of Astronomy.*

The sun is discussed in considerable detail on pages 213–214, including the present conception of the origin of the sun's energy.

. Menzel, Donald H., *Stars and Planets.* New York: The University Society, 1938.

The student will find it hard not to read this entire volume. Chapter V considers the sun.

. Abbot, C. G., *The Earth and the Stars.* New York: The D. Van Nostrand Company, 1925.

The author treats the sun in greater detail than the authors of the references above. The presentation is not too technical, however, for the general reader. Chapters XII and XIII consider the sun itself. Chapter XIV considers the subject of energy from the sun, describing experimental attempts to utilize the heat of the sun directly.

19

The Measurement of Energy

THE STORY of the liberation of man from the drudgery of prolonged har physical labor is the story of the development of machines. All earl civilizations were based to a large extent upon the institution of slaver The pyramids, for example, represent the work of literally hundreds thousands of slaves. Slavery as an institution, except perhaps in time war, is a thing of the past, not because it was immoral or cruel, but becaus modern machines are more efficient, need fuel only when actually workin are tireless, and, most important, are cheaper to operate than slave powe Many electric light companies have been boosting the sale of electricit with the slogan, "You can do it better and cheaper with electricity. This slogan has some scientific basis. For example, a farmer finds it nece sary to pump water for irrigation purposes during a period of drough A pump is installed and is operated by a laborer whom the operator agre to pay three dollars per eight-hour day. It is estimated that an averag man can do work at the rate of about one-seventh horsepower. If a on seventh horsepower motor were substituted for the laborer, the cost continuous operation during an eight-hour day would not exceed ten cent Furthermore, the laborer working for three dollars a day will find it in possible to work as continuously or as steadily as the untiring electr motor. The workman and the motor require energy to perform wor Energy is the capacity for doing work. It is energy which makes possib modern machines. The complexities of our modern machine age are du to our present understanding of the nature of energy and to the develo ment of machines to utilize energy in an ever-increasing variety of way

How Energy Is Measured

It will be shown that work results in useful accomplishment. Work performed if we move an object from one place to another, stop a car th is in motion, or make a car move faster. Energy is needed to do wor Hence, the methods for measuring energy depend upon the amount of wo resulting from the use of energy. It is evident, then, that the amount work accomplished depends upon the *magnitude* of the force that is applie

ıd the *time* of application of the force which produces a *change in motion* or *sition* of a body, or the *distance* through which the force is applied. Since is usually easier to measure distance experimentally than to measure ne, work is measured in terms of the force applied and the distance rough which it acts.

$$W(\text{ork}) \propto F(\text{orce})$$
d $$\propto D(\text{istance}).$$

is means, then, that

$$W \propto FD$$
$$W = kFD.$$

y inventing suitable work units, the numerical value of the proporonality constant (k) can be made unity. Thus, if F is one poundal and is one foot, the work unit is called the *foot-poundal*. If F is one dyne d D is one centimeter, the work unit is called the *dyne-centimeter* or *erg*. is unusual term was coined by using a part of the word en-*erg*-y. The g is a very small unit; therefore, a much larger unit, the *joule*, is also quently used. It is equal to 10^7 or ten million ergs.

The defining relationship for the measurement of work and energy in jective terms, then, becomes $W = F \times D$ in foot-poundals or ergs, proded the force is expressed in poundals or dynes, and the distance in feet or centimeters, respectively. The force included in this definition is only the force which is exerted in the *same direction* as the motion which results.

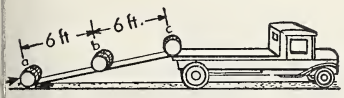


FIGURE 220
CLINED PLANE APPLIED IN LOADING

For example, the amount of work performed in rolling a barrel six feet up the incline in Figure 220 is exly half that required to roll it up the entire length of the incline, a tance of twelve feet. If, therefore, the force F needed was sixteen hund poundals, the work in rolling the barrel from a to b would be,

$$W_b = F \times D_b = 1600 \text{ poundals} \times 6 \text{ ft}$$
$$= 9600 \text{ foot-poundals.}$$

t to roll the barrel the entire length of the incline (c) the work required uld be

$$W_c = F \times D_c = 1600 \text{ poundals} \times 12 \text{ ft}$$
$$= 19{,}200 \text{ foot-poundals.}$$

nilarly, if the barrel weighed twice as much, the force necessary would thirty-two hundred poundals, and the work required to roll it on to the ck platform would also be increased by a factor of two; that is,

$$W = 3200 \text{ poundals} \times 12 \text{ ft}$$
$$= 38{,}400 \text{ foot-poundals.}$$

Potential and Kinetic Energy

The sport of skiing will serve to bring out the meaning of potential an kinetic energy. (See Figure 221.) To trudge from the bottom *a* to th top *d* of the hill with one's skis requires a personal expenditure of effo (energy). Path *b* is not nearly so steep as path *c*, and might seem easi to climb because the personal expenditure of effort in a given time will b considerably greater in certain parts of path *c*. The naïve explanation to say that path *c* is steeper and hence more difficult. However, paths *b* and *c* have one characteristic in common: in traveling from *d* to *a*, the change in elevation is identical. It has been shown in Chapter 12 that bodies fall or travel down an incline because of the attraction of gravity. Conversely, to raise a body from level *a* to level *d*, by any route whatever, requires the continuous application of force, since the force of gravity is always acting, and this means an expenditure work or energy. The amount of energy involved in this change can b calculated:

FIGURE 221. SKI SLIDES
Difference in level, not length of path, determines potential energy

$$W = F \times D = mgh \text{ ergs, or foot-poundals.}$$

A person climbing the hill from *a* possesses something in position *d* th he has gained — it is called *potential energy*. Potential energy is usual defined as the energy that a body possesses as a result of having son agency do work upon it. This usually results in a change in the *configur tion* or *position* of the body with reference to its original condition or po tion. When one does work against the attraction of gravity, as when skier climbs a hill, the body acquires potential energy. The amount potential energy thus acquired is explicitly measured by the relationshi

$$P(\text{otential})\ E(\text{nergy}) = F \times D = mgh \text{ (or mass} \times g \times \text{vertical height)}$$

If the mass of the body is in pounds, g in feet per second, and the verti height through which the body is raised is expressed in feet, the potent energy is expressed in foot-poundals. In c.g.s. units, m must be express in grams, g in centimeters per second, and h in centimeters, and the pote tial energy will be in dyne-centimeters, or ergs. Note that in fundame tal units, the foot-poundal is indicated by the symbol lb-ft^2/sec^2, and t erg by g-cm^2/sec^2.

It is proper to ask what becomes of the potential energy of the skier he glides down the hill. When the skier reaches the bottom of the hill a coasts along the level, he has lost all his potential energy; but that he st possesses energy is obvious, since it requires an application of force (e

enditure of energy) to bring him to rest. The energy that a body ossesses by virtue of its motion is called *kinetic energy*. The operation driving a nail with a hammer illustrates the relationship between these rms of energy. With a portion of the energy stored in the human body, ie arm can impart motion to a hammer. The head of the hammer now ossesses kinetic energy, and the latter is utilized to drive the nail into wood, an operation requiring an expenditure of energy. Similarly, water at the brink of a waterfall possesses potential energy. As it starts to fall, the potential energy is steadily converted into kinetic energy. The energy of the water at the bottom of the falls will be entirely kinetic, and can be utilized, for example, in a water turbine to generate electrical energy. Hence we see that potential energy is convertible into an equivalent amount of kinetic energy. This equivalency of potential and kinetic energy serves as a simple method of evaluating the magnitude of the energy of a moving body. Thus, the energy of a body with mass m in position a (Figure 222) is entirely potential; in position b after having fallen the distance h, e energy is entirely *kinetic*, and the two are equivalent to each other. ence,

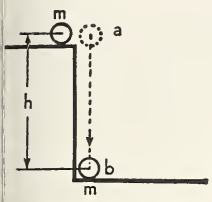


FIGURE 222
OTENTIAL AND KINETIC ENERGY
The potential energy ergy of position) at a *uals the kinetic at* b. *e former is static; the ter dynamic.*

$$K.E. \text{ at } (b) = P.E. \text{ at } (a) = mgh \tag{1}$$

is object is a freely falling body moving under the influence of gravity. ie vertical height h through which the body falls is related to the time of lling as follows: $h = \frac{1}{2} gt^2$. Hence, in Equation (1) we can make a simple bstitution which gives

$$K.E. = mg\left(\tfrac{1}{2} gt^2\right) = \tfrac{1}{2} m\,(gt)^2 \tag{2}$$

is customary, however, to express kinetic energy in terms of mass and locity. But the velocity v of a falling body depends only upon the celeration due to gravity and the time t, or

$$v = gt$$

d

$$v^2 = (gt)^2$$

ence, making a substitution in Equation (2),

$$K.E. = \tfrac{1}{2} mv^2 \text{ in foot-poundals or ergs.}$$

It is essential that the student understand how to use the expressions potential and kinetic energy. Consider these examples:

1. A person with a body weight of 150 lbs climbs a cliff until he is thirty- feet above the surface of the water. What potential energy does he ssess?

SOLUTION: $P.E.$ = work expended in climbing vertically 36 feet
$= mgh = 150 \text{ lb} \times 32 \text{ ft/sec}^2 \times 36 \text{ ft}$
$= 172{,}800 \text{ lb-ft}^2/\text{sec}^2$
or $= 172{,}800$ foot-poundals

2. If the person in the above exercise dives into the water, what is his potential and kinetic energy when he strikes the water?

SOLUTION: His potential energy becomes zero as he enters the water. His energy is then entirely kinetic and must be equivalent to the original potential energy, or 172,800 foot-poundals. However, if one calculates the velocity after falling the distance of thirty-six feet, the kinetic energy can be calculated: Since $h = \frac{1}{2} gt^2$, it follows that the time needed to fall thirty-six feet is,

$$t = \sqrt{2h/g} = \sqrt{\frac{2 \times 36 \text{ ft}}{32 \text{ ft/sec}^2}}$$

$$= \sqrt{2.25 \text{ sec}^2} = 1.50 \text{ sec}$$

Hence the velocity at the time of striking the water is expressed as $v = gt$, or

$$v = 32 \text{ ft/sec}^2 \times 1.50 \text{ sec} = 48.0 \text{ ft/sec},$$

and $K.E. = \frac{1}{2} mv^2 = \frac{1}{2} \times 150 \text{ lb} \times (48.0 \text{ ft/sec})^2 = 172{,}800$ foot-poundals.

3. What force is exerted by a catcher in stopping a five-ounce ball traveling 50 ft/sec, if we assume a "follow through" of six inches?

SOLUTION: It is important to realize that the force exerted by the catcher depends upon the stopping distance. The force needed would be infinitely large if the stopping distance were made infinitely small. Every catcher has learned by experience the necessity of moving the hands backward a short distance before bringing the ball to a dead stop. In this problem the stopping distance is assumed to be six inches.

The solution of this problem lies in realizing that the work performed in stopping the ball must be equal to the kinetic energy possessed by the moving ball, or

$$K.E. \text{ of ball} = \tfrac{1}{2} mv^2 = \tfrac{1}{2} (\tfrac{5}{16} \text{ lb}) (50 \text{ ft/sec})^2 = 391 \text{ foot-poundals}.$$

Note that it was necessary to change the mass in ounces to pounds (16 oz = 1 lb). If F represents the stopping force exerted by the catcher, then the work expended in stopping the ball is

$$W = F \times D = F \times \tfrac{1}{2} \text{ ft},$$

and $F \times \frac{1}{2}$ ft = 391 foot-poundals,

or $F = 391 \times 2 = 782$ poundals.

Relation Between Pound and Poundal

The pound is a unit of mass; the poundal, a unit of force; and the foot-poundal, a unit of work or energy. Keep these distinctions always in

nd when solving problems involving work. The minimum amount of rce that must be applied to lift a one-pound mass is that necessary to ercome the attraction of the earth, or

$$F = mg = 1 \text{ lb} \times \frac{32 \text{ ft}}{\text{sec}^2} = \frac{32 \text{ ft-lb}}{\text{sec}^2} = 32 \text{ poundals.}$$

ence, a force of thirty-two poundals ll support a one-pound mass. In the ird example above, the force needed to op the ball was 782 poundals, which is force large enough to support a mass 782/32, or 24.4 pounds.

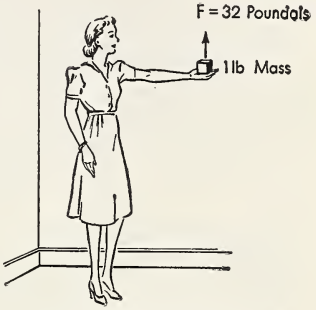


FIGURE 223. A FORCE OF THIRTY-TWO POUNDALS SUPPORTS A MASS OF ONE POUND

pes of Energy

Energy, then, represents the capacity r doing work. For purposes of classi- ation and measurement, energy is of ur types, *potential*, *kinetic*, *radiant*, and dinary *matter*. The energy which reams to us from the sun travels with e velocity of visible light, and is re- onsible for all plant growth, the circu- tion of the atmosphere, the evaporation of water from the oceans, and her significant changes. It is called radiant energy. This energy is not sociated with ordinary matter as it travels through space. Because of s unusual character, a full discussion of radiant energy is postponed to hapter 44. Likewise the implications of matter as energy will be post- oned to Chapter 25.

The radiant energy from the sun eventually assumes many different rms on the earth. Some of this energy is absorbed by the oceans to come ordinary heat, which evaporates water from the oceans into the mosphere. The water vapor possesses *energy in the form of heat* and also nother kind of energy as a result of being lifted against the pull of gravity - *potential energy*. Eventually, some of this water cools to form snow n some inland mountain range. Here it absorbs more heat from the sun, hanges to a liquid which collects in streams and starts on its way back o the sea. Much of its energy is now *kinetic energy* — water in motion. n its way to the sea this fast-flowing water may pass through the turbines a hydroelectric plant. Here the water loses some of its kinetic energy, hich reappears as *electrical energy*. Electricity is energy because it is sed to perform work in operating trains, elevators, or vacuum cleaners.

Plants cannot grow without a continuous supply of energy from the sun, hich the plant uses to produce starch or cellulose. Starch and other plant oods are the ultimate source of energy for all animals. This energy from

the sun remains with the plant structure even though the latter may b converted into coal. Coal still retains the capacity for furnishing energ in the form of heat, and this capacity represents still another form of energ — *chemical energy*. The storage battery of an automobile does not contai electricity as such, though it has a certain capacity for furnishing electrica energy. It possesses chemical energy. The energy locked within an ato in the form of charges of electricity is now called nuclear energy. Thi was the kind of energy that made the atomic bomb possible.

In reality the various forms of energy are fundamentally variations o the different types of energy. Merely to serve as a preview of what is t follow in succeeding chapters, the relations between the various types an forms of energy are tabulated here:

PREVIEW OF ENERGY

Types:	1. Potential	2. Kinetic	3. Radiant	4. Matt
How measured?	$PE = mgh$	$KE = \frac{1}{2} mv^2$	$E = hf$	$E = m$
Units:	1. Foot-poundal 2. Erg 3. Joule 4. Calorie			
Forms:	1. Chemical	2. Heat: due to motion of molecules 3. Electricity: due to motion of electrons		
	4. Nuclear			

The Significance of Machines

Energy *per se* cannot accomplish useful work; it requires a machine o which or through which to operate. The first machine was man himself, device to utilize the chemical energy of food in order to carry on the task of life. Man is the only animal which consciously uses energy other tha that from his body to do the tasks of life. Primitive man domesticate certain wild animals to serve as beasts of burden or sources of energy For a long time during the early history of man, the only machines fo performing work were men — freemen or slaves — and domesticated an mals. History does not record when early man discovered the usefulnes of the wheel, the inclined plane, the lever, and other simple machine but the effects were far-reaching. With a simple inclined plane, for exam ple, man can move a very heavy object by the expenditure of a relativel small force.

Civilization began when early man increased the effectiveness of his ow

orts by utilizing *simple machines*, which we now recognize as six in mber: the inclined plane, the lever, the pulley, the screw, the wheel d axle, and the gear. Modern man has added two other types of very portant machines: the various ones (the motor, electric light, and trans- mer) that depend for their operation upon electrical energy; and the at engine. These will be discussed in Chapters 21 and 39.

Intrinsically, a machine is a device which, if supplied with energy, called e *input*, will result in transformations so that the energy which comes t of the machine, called the *output*, yields certain desirable effects. A v examples are listed below.

(1) *The electric light bulb.* The input is electrical energy; the output is ht and heat.

(2) *An electric motor.* The input is electrical energy; the output is the tion of a pulley — kinetic energy.

(3) *The inclined plane.* The input involved in the operation of an lined plane usually consists of a relatively small force acting through a ge distance, while the output consists of a relatively large force acting rough a short distance. In effect, then, the inclined plane results in a ltiplication of forces.

For example, in Figure 224, the highway comes to the river's edge. In ler to eliminate the inconvenience of a ferry, a bridge with an elevation twenty feet is constructed to carry the traffic across the river. An in- ned plane six hundred feet in length is a necessary accessory. To lift a 00-pound car directly upward from level a to level b would require a atively large force,

$$F_2 = mg = 3000 \text{ lbs} \times 32 \text{ ft/sec}^2 = 96{,}000 \text{ poundals}.$$

e force F_1 needed to urge the car uniformly along the inclined plane, wever, is very much less. If we call the energy utilized in driving the up the incline the input, we can write,

$$\text{Input} = (F_1)\ (600 \text{ ft}).$$

e output represents the effective result, the lifting of the car twenty t against the pull of gravity.

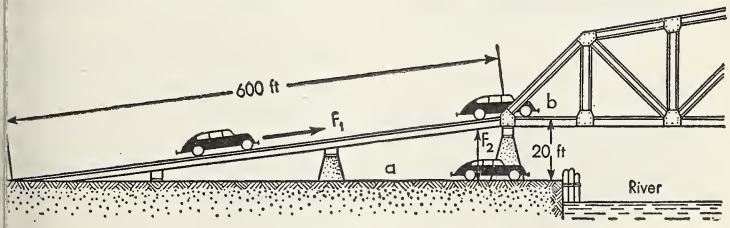


FIGURE 224
ILLUSTRATING THE FORCE FACTOR AND THE DISTANCE FACTOR

Hence,

$$\begin{aligned}\text{Output} &= F_2 \times h = mgh \\ &= 3000 \text{ lbs} \times 32 \text{ ft/sec}^2 \times 20 \text{ ft} \\ &= 1{,}920{,}000 \text{ foot-poundals.}\end{aligned}$$

But, since no other forces have been involved, it must be theoretically tru neglecting force needed to overcome friction, that

$$\text{Input} = \text{Output, and}$$

$$(F_1)\ (600 \text{ ft}) = 1{,}920{,}000 \text{ ft}^2\text{-lbs/sec}^2,$$

or

$$F_1 = 3200 \text{ poundals.}$$

The significance of this answer is apparent when compared with th 96,000 poundals needed to lift the car vertically. A machine transform energy called the input into energy with other characteristics called th output. The output, therefore, cannot exceed in amount the input, u less we are to get something for nothing. This explains why the outp was made equal to the input in the above problem.

In discussing the inclined plane, economy of effort will result if we co ventionalize the treatment by letting *W*(eight) represent the object bei raised a vertical height *h*, by the application of a *F*(orce) along an incline plane of length *l*. Now, further analyze the problem given above, an note the values of the following ratios:

$$\frac{W}{F} = \frac{\text{Weight of object}}{\text{Force along the plane}} = \frac{96{,}000 \text{ poundals}}{3200 \text{ poundals}} = \frac{30}{1}$$

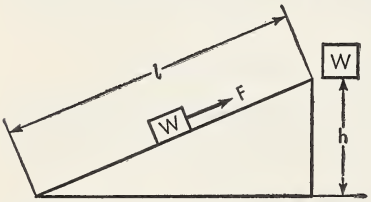


FIGURE 225. THE PRINCIPLE OF THE INCLINED PLANE

$\frac{W}{F} = \frac{l}{h}$ *in an ideal inclined plane*

$$\frac{l}{h} = \frac{\text{Length of plane}}{\text{Height of plane}} = \frac{600}{20} = \frac{30}{1}$$

The ratios are called the *mechanic advantage* of the inclined plan Since,

$$\frac{W}{F} = \frac{l}{h} \text{ (neglecting friction),}$$

it follows that as the ratio of th length of the plane to its heigh l/h increases, the force necessar to move an object along the plan decreases. Thus, if the incline a proaching the bridge in Figure 2 were doubled in length, the for then necessary to move the c along the plane, would decrease 1600 poundals.

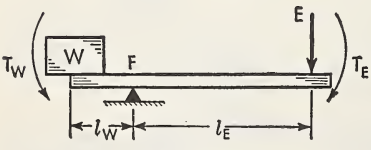


FIGURE 226
THE PRINCIPLE OF THE LEVER

(4) *The lever.* Such common d vices as pincers, shears, nutcracker

nd wrenches make use of various forms of the lever. The simplest form f a lever consists of a straight, rigid bar arranged to rotate about a point alled the *fulcrum*, F in Figure 226. For simplicity's sake, it is assumed hat the weight of the bar is negligible. If a weight W is placed at a dis- ance l_w from the fulcrum, there will be a tendency for the weight and the ever to rotate in a counter-clockwise manner about F. Man has found rom experience that the rotation can be prevented by applying another orce E(ffort), somewhere along the lever on the other side of the fulcrum. hus we have two opposing tendencies to produce rotation, and these are esignated *torques*. The effectiveness of a torque in producing rotation epends upon two factors, the size of the force and the length of the lever rm, or

$$\text{Torque} = \text{Force} \times \text{lever arm}.$$

he magnitude of torque T_E, which tends to produce clockwise rotation, given by the expression

$$T_E = E \times l_E.$$

imilarly, the opposing torque is equal to

$$T_W = W \times l_w.$$

y suitable selection of either the magnitude of E, or of its lever arm l_E, he two torques can be made equal, and the system will be in a condition equilibrium. Then,

$$T_E = T_W, \text{ and}$$
$$E \times l_E = W \times l_w, \text{ or}$$
$$\frac{W}{E} = \frac{l_E}{l_w}.$$

hese ratios are called the mechanical advantage, or multiplying power, the lever.

The common crowbar is a good ustration of a lever in which the echanical advantage is relatively rge because the ratio of the effort- ver arm to the resistance-lever rm is also relatively large. (Com- are Figure 227 with Figure 226.) typical crowbar is made of steel in

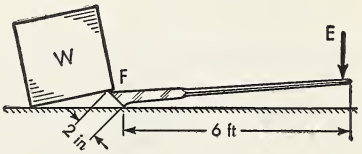


FIGURE 227. A CROWBAR

ich a way that it will rock about the line F, which serves as the fulcrum. the distance from the point of application of the effort E to the fulcrum six feet, and the distance from F to very close to the tip, is two inches, follows that the mechanical advantage,

$$MA = \frac{l_E}{l_w} = \frac{6 \times 12}{2} = 36.$$

This means that the application of an effort force E of one hundred pounds should balance a load W on the end of the crowbar with a force equivalent to a mass of thirty-six hundred pounds.

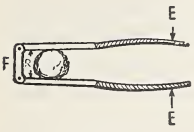


FIGURE 228
A NUTCRACKER

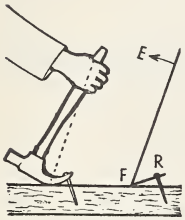


FIGURE 229
A CLAW HAMMER
PULLING OUT A NAIL

Our lever in Figure 226 is an ideal lever in that it is rigid, straight, and weightless. Actual levers are seldom straight and assume many different forms. However, careful examination will reveal the elements of the lever. (Refer to Figures 228 and 229.)

Reference has been made to other simple machines — the pulley, the screw, the wheel and axle, and the gear. These are familiar elements in modern machines, whether watches or tractors. The mechanical advantage of these machines can be deduced from their geometrical design, since they can all be regarded as levers or inclined planes. (Refer to Table 25.) In the various equations in this table, W denotes resistance or weight lifted, E denotes effort or force applied, and r stands for radius.

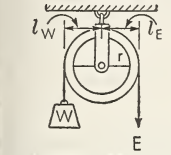
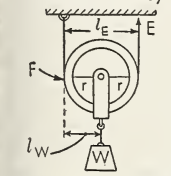
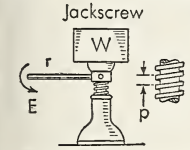
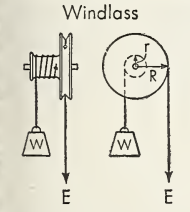
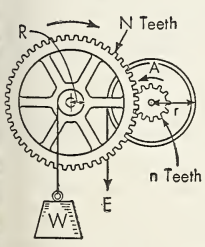
The speed and efficiency with which the activities of our modern civilization are conducted are possible because of machines. The development of the automobile, for example, has had profound social and economic effects. To many the modern automobile seems an exceedingly complex device. But anyone who will take the time to examine it carefully can convince himself that it simply contains the different types of machines that we have discussed in this chapter, namely, the lever, the pulley, the wheel and axle, the inclined plane, the gear, the screw, and the engine which converts one form of energy into another.

Actual Machines Are Not Perfect

Throughout the discussion of machines thus far, the assumption has been made, for purposes of simplification, that the machine is a perfect machine, that the energy output is equal to the energy input. Actually there are imperfections in the operation of real machines, and the output is always *less* than the input. The ratio of the output to the input is referred to as the mechanical efficiency, and only in a perfect machine could this ratio be unity, or one hundred per cent.

$$\text{Mechanical efficiency} = \frac{\text{work performed by a machine}}{\text{energy supplied the machine}} = \frac{\text{output}}{\text{input}}$$

Table 25. Some Common Simple Machines

Name	Contains What Simple Machine	Mechanical Advantage (Neglecting Friction)	
Fixed Pulley 	Lever	$\frac{W}{E} = \frac{l_E}{l_W} = \frac{r}{r} = 1$	Used principally to effect a change in direction of application of force
Movable Pulley 	Lever	$\frac{W}{E} = \frac{l_E}{l_W} = \frac{2r}{r} = 2$	Movable pulleys often used in blocks of 2-4 pulleys; each movable pulley multiplies mechanical advantage by 2
Jackscrew 	Lever and Inclined Plane	$\frac{W}{E} = \frac{2\pi r}{p}$ p = Thickness of One Thread	Employed in auto jack, common meat grinder, etc.
Windlass 	Lever	$\frac{W}{E} = \frac{2\pi R}{2\pi r} = \frac{R}{r}$	Numerous applications in machinery, as hand brake on a street car
Gear 	Lever	$\frac{W}{E} = \frac{r}{R} \times \frac{N}{n}$	Very frequently used

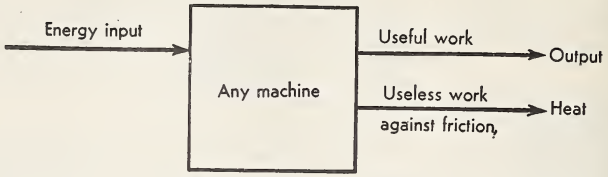


FIGURE 230. INPUT = OUTPUT + WORK LOST BY FRICTION

The energy obtained in the form of motion from the average steam loco motive as compared with the energy supplied in the form of coal is so lo that the efficiency is often less than five per cent. On the other hand, th efficiency of a well-designed lever system is almost one hundred per cen

The failure of a machine to achieve perfect efficiency can be ascribed t useless work or *friction*. What becomes of the energy that does not appea as useful work? In all machines, wasted energy or work appears in th form of *heat*. An electric motor, if perfect, would remain at the same tem perature as its surroundings. Actually, an operating motor is alway warm, and the less efficient the motor, the warmer it is. A vessel of wate shaken vigorously is warmed; a stiff band of metal rapidly flexed gets warm or even hot. You can perform the experiment of rapidly rubbing th palms of your hands against each other and determine for yourself tha work against friction generates heat. These results are summarized i Figure 230.

The operation of any machine requires that energy in some form b continuously supplied to the machine. This is the input, which usuall must be purchased. The fuel needed to operate a Diesel train, for ex ample, must be charged against the cost of operation. Efficiency demand that the value of the ratio,

$$\frac{\text{output}}{\text{cost of energy input}}$$

must be as large as possible. There are only two ways of bringing abou this result. One is to use the cheaper forms of fuel; the other is to increas the mechanical efficiency of the machine itself by cutting down the fractio of the energy converted into useless work or heat. Modern technolog accomplishes this result by using jeweled, ball, and roller bearings in eve increasing numbers.

The common sources of energy, arranged in the order of increasing co per unit of energy, are:

Sunlight
Coal
Natural gas
Petroleum
Artificial gas
Electricity
Nuclear, or atomic

ith the exception of sunlight, the consumer must purchase these forms energy. This necessity has led to one of the great delusions of the me- anical age: the search for a machine so free of friction that after it is ce started in motion, it will keep going forever. This is the delusion of erpetual motion" in a machine designed to perform work. Hundreds applications for patents on so-called perpetual-motion machines have en submitted to the Patent Office, and all have been rejected, because he law of the machine" rules out the possibility of such a machine. In her words, there can be no output without input.

w of Conservation of Energy

The truth just stated in reality constitutes one of the most fundamental inciples in science. It is usually referred to as the Law of Conservation Energy, or the Law of the Machine. Energy can be neither created nor stroyed, and when a certain amount of one kind of energy disappears in e place, an equivalent amount of some other kind of energy appears mewhere else. This principle is so broad and has so many applications at its true significance will be better appreciated after one has seen some its myriad applications. The experimental basis for this principle will presented later in connection with the study of heat.

SUMMARY

1. Energy represents the capacity for performing work. Some common forms are heat, electrical, chemical, and nuclear.
2. Work results whenever force is applied to any object through a measurable distance. Work, therefore, represents the effective application of force in the sense of changing the position or motion of a body. The common units of work are the foot-poundal, the erg, and the joule. The defining relationship for work is $W = F \times D$.
3. Potential energy is the energy possessed by a body as the result of having some agency do work upon it to change its configuration or position with reference to its original condition or position. The potential energy of a body which has been elevated against the attraction of the earth is given by $P.E. = mgh$ foot-poundals or ergs.
4. The energy of a body due to motion is called kinetic energy. Kinetic energy in foot-poundals or ergs is given by $K.E. = \frac{1}{2} mv^2$.
5. The force needed to support a one-pound mass against the pull of gravity is approximately thirty-two poundals. Similarly, the force needed to support a one-gram mass is approximately 980 dynes.
6. Machines enable man to perform tasks that otherwise would be impossible and enable him to work with energy other than that supplied by himself.
7. Machines are of two types: simple machines — lever, inclined plane, pulley, screw, wheel and axle, gear — and the machines which convert one form of energy into another.

8. The mechanical advantage of a simple machine is a number which is an ind cation of its effectiveness in decreasing the effort necessary to perform a give task. The mechanical advantage of any machine is given by the ratio:

$$\frac{\text{Weight of object moved}}{\text{Effort applied}} = \frac{W}{E}.$$

The mechanical advantage of a frictionless inclined plane and a lever a given by the ratio:

$$\frac{\text{length of plane}}{\text{vertical height}} = \frac{l}{h},$$

and

$$\frac{\text{lever arm of effort}}{\text{lever arm of weight being moved}} = \frac{l_E}{l_W}.$$

9. The effectiveness of a force in producing rotation about a center is called i torque. It is numerically equal to the product of the applied force × lev arm.

10. Only in perfect machines can the output equal the input. In any real m chine, the output is always less than the input because of useless wo against friction. The latter energy is converted into heat.

The mechanical efficiency of a machine is given by the ratio $\frac{\text{output}}{\text{input}}$.

11. The principle that the output of a machine cannot exceed the input, is know as the Law of Conservation of Energy. Another common statement of t law: Energy can neither be created nor destroyed; when a certain amount energy disappears in one place, an equivalent amount appears somewhe else.

STUDY EXERCISES

1. At the right appear certain terms or scientific expressions. Associate the by number with the definitions or statements given at the left.

.... That which represents the capacity for doing work.
.... The expression often used as a defining relation for work.
.... A common unit of force.
.... The work performed when a force of one dyne operates through a distance of one centimeter.
.... The fundamental English absolute unit of work.
.... The unit of work in the English system that corresponds to the erg in the c.g.s. system.
.... The kind of energy that a body possesses as a result of its position with respect to the surface of the earth.
.... The kind of energy possessed by a moving body.

1. Conservation of energy
2. Kinetic energy
3. Potential energy
4. $\frac{1}{2}mv^2$
5. Foot-poundal
6. Mechanical advantage
7. $F \times d$
8. Erg

. . The kind of energy that a body possesses as a result of doing work upon it in such a way that the energy is recoverable.	9. Energy
. . . The expression used to measure potential energy.	10. Poundal
. . . The expression used to measure kinetic energy.	11. *mgh*
. . . The ratio of the resistance to the effort in a simple machine.	12. Efficiency
. . . The ratio of the useful work obtained from a machine to the total amount of energy supplied to the machine.	
. . . The principle which states that it is hopeless to try to construct a machine which is so free from friction that it will be possible to get "something for nothing."	

2. (*a*) A 50 lb load was carried to the top of a building 64 ft high. Encircle correct answers.

(1) What was the force in poundals that had to be exerted by the carrier?
50 poundals. 1600 poundals. 3200 poundals.

(2) What work was expended by the carrier in taking it to the top of the building?
1600 poundals. 102,400 poundals. 102,400 ft-poundals.

(3) If the carrier had paused for rest at the 32-foot level and then continued to the top, would the amount of work necessary to be expended be the same, more, or less?
Same. More. Less.

(*b*) The load was then allowed to fall.

(1) How far will the object fall in one second?
16 feet. 32 feet. 64 feet.

(2) How far will the object be from the ground after one second?
0 feet. 32 feet. 48 feet.

(3) What will be the velocity after falling one second?
16 ft/sec 32 ft/sec 48 ft/sec

(4) What will be the kinetic energy of the object after falling one second?
32 ft-poundals. 76,800 ft-poundals. 25,600 ft-poundals.

(5) What will be the potential energy after falling one second?
32 ft-poundals. 76,800 ft-poundals. 25,600 ft-poundals.

(6) How does the sum of the kinetic energy and the potential energy after falling one second compare with the original potential energy?
Same. Less. More.

(7) How long a time will elapse before the object reaches the ground?
1 second. 2 seconds. 3 seconds.

(8) What will be its velocity when it reaches the ground?
32 ft/sec. 64 feet. 64 ft/sec.

(9) What will be the kinetic energy just as the object reaches the ground?
0 ft-poundals. 102,400 poundals. 102,400 ft-poundals.

(10) What will be the potential energy just as the object reaches th ground?
0 ft-poundals. 102,400 poundals. 102,400 ft-poundals.
(11) How does the kinetic energy just as the object reaches the groun compare with the original potential energy?
Less. More. Same.
(12) What transformation of energy occurs as the swiftly moving objec collides with the ground?
Kinetic energy is converted into potential.
Potential energy is converted into kinetic.
Kinetic energy is converted into heat.

3. Explain how Problem 2 illustrates the law of conservation of energy.
4. Examine closely a common household mechanical device, such as an eg beater or the thermostat on a furnace. How many examples of simple ma chines do you find have been used in its construction? (Refer to page 357.)
5. A truck ramp at a freight station rises five feet for every one hundred fe along the ramp.
(*a*) What is the mechanical advantage?
(*b*) If the truck and its load weigh four tons ($4 \times 2000 \times 32$ poundals), wh is the minimum force needed to hold the truck stationary on the ram
(*c*) Will the actual force needed to cause the truck to move up the ramp the same as the calculated minimum force, or more? Explain.
6. A common way to get hot water in a home is to place a hot water heati coil in the furnace. The owners of many such coils believe that this h water is obtained at no cost because they have to operate the furnace an how. Apply the law of conservation of energy to this situation. Is the ope ator of such a coil really obtaining hot water at no cost to himself?

FOR FURTHER READING

1. Lemon, H. B., *From Galileo to the Nuclear Age.*
The author in a very entertaining manner presents the fundamental notio concerning matter and energy. Chapters 9, 10, and 11 consider the meaning work and energy, potential and kinetic energy and their measurement, and t law of conservation of energy.
2. Mott-Smith, M., *This Mechanical World.*
This little volume presents with a minimum of mathematics the importa contributions of Archimedes, Galileo, and Newton. Chapter XVII deals wi potential and kinetic energy.
3. Dunning, J. R., and H. C. Paxton, *Matter, Energy and Radiation.* Ne York: McGraw-Hill Book Company, 1941.
Chapter VI has an excellent discussion on "Ideas about Energy."
4. Stephenson, R. J., *Exploring in Physics.*
The methods to follow in computing potential and kinetic energy, mechanic advantage, mechanical efficiencies, and conversion of work into heat in conne tion with actual machines are presented in Chapter 5. There are many inte esting problems.

20

Heat: The Energy of Life

EAT IS THE FORM OF ENERGY associated with life. It was the discovery how to kindle a fire that made it possible for primitive man to migrate rthward away from the tropics, for only with fire could he dispel the mpness of his cave home and provide it with warmth during the winter ason. The discovery of the methods of making fire was one of the truly eat discoveries of all time. The countless benefits of fire have made so any imprints on man's unconscious self during past time that universally day we take a fire crackling in the fireplaces of our homes as the center home life, as something to inspire confidence and security. In an era air-conditioned homes, however, a fireplace will be an anachronism diffi-lt to justify except on the basis of sentiment.

Reverence for fire was an essential part of many primitive religions. he early Greeks considered all matter as manifestations of only four rimordial substances, earth, water, air, and fire. The alchemist of the liddle Ages resorted to the use of fire in his search for gold, the only metal ien known that would withstand the effects of intense heat. The myriad iemical changes employed by the modern chemist in making better dyes, edicinals, textiles, would not be possible without the aid of heat. It was ie development of the steam engine that brought about the Industrial evolution, when mechanical power was widely substituted for the power of en and animals. The first heat engine with greater mechanical efficiency ian the steam engine was the internal combustion motor. The most cent improvement in heat engines is the Diesel engine. Finally, it is eat that enables our bodies to continue to function. As has been stated efore, the human body is essentially an engine for transforming the iemical energy of food into work and heat.

Common Heat Phenomena

Before attempting to discuss the nature of heat as energy, it will be ecessary to note briefly certain facts or phenomena concerning the origin nd effects of heat.

Matter when heated increases in volume. Practically all solids, liquids and gases expand in all directions with an increase in temperature. In general terms, gases expand more than liquids, and liquids expand more than solids. The rate of expansion of gases is unusual in that it is nearly the same for all gases. Thus, one hundred cubic feet of air or any other gas at the temperature of melting ice, if heated to the temperature of boiling water, expands to a volume of about 136.6 cubic feet.

The amount of expansion is difficult to perceive at times, but modern technology gives many examples of phenomena in which expansion is involved. Long steam pipes must be built to allow for expansion. If an automobile engine is operated with insufficient oil, it will become so warm that the pistons will "seize" the cylinder as a result of abnormally large expansion and stop operating. The standard meter in the Bureau of Standards, Washington, D.C., is kept at the temperature of melting ice 0° C., in order to keep its length constant. During periods of hot weather concrete highways sometimes shatter as a result of unusually great linear expansion. The sag in electric power lines is considerably greater in summer than in winter because of expansion. Long steel bridges should always be placed on rollers to allow for expansion. (Refer to Figure 231. One of the difficulties that had to be overcome in the perfection of the

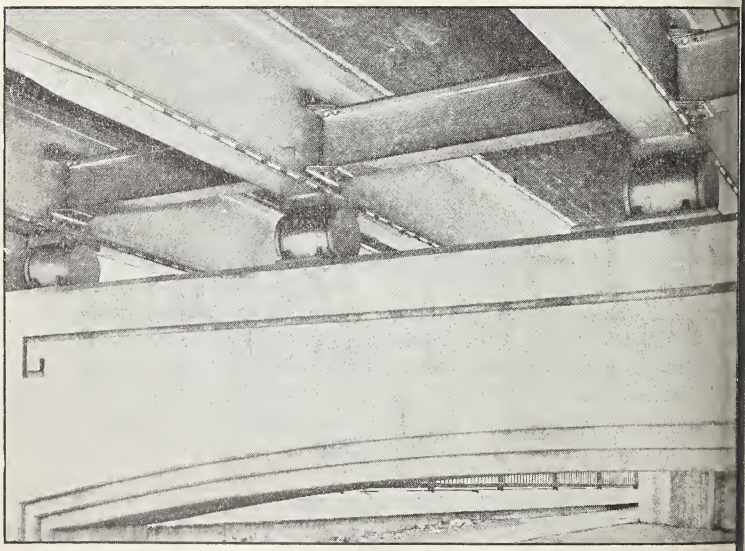


FIGURE 231. LONG BRIDGES ARE PLACED ON ROLLERS
(*Courtesy of W.P.A. Museum Project No. 3702*)

lectric light bulb was to prevent leakage of air where the wires carrying he current pass through the glass bulb. Edison solved the problem with latinum wire, since this metal and glass expand at the same rate, but hese "lead-in" wires are now made of invar, an alloy of nickel and iron.)ne of the important factors in the geological process of weathering is the isintegration of rocks as a result of alternate expansion and contraction ollowing temperature changes.

A conspicuous exception to the general rule that the addition of heat esults in an increase in volume is ordinary water. If water at the tem- erature of melting ice, 0° C., is gradually heated, the volume decreases ntil a temperature of 4° C. is reached. This means, of course, that the ensity of water increases with increase in temperature from 0° to 4° C. 'he volume of a kilogram of water and the density at four temperatures re given in Table 26.

TABLE 26

Temp. C.	Volume 1 kg water — cm^3	Density g/cm^3
0°	1000.13	0.99987
4°	1000.00	1.00000
10°	1000.27	0.99973
20°	1001.77	0.99823

Jote that the density increases as the volume occupied by a given mass of ater decreases. Density in this case merely means the mass in grams f one cubic centimeter. Using the data for 0° C.,

$$\text{density} = \frac{M(\text{ass})}{V(\text{olume})} = \frac{1000\ \text{g}}{1000.13\ \text{cm}^3} = 0.99987\ \text{g/cm}^3.$$

The behavior of water on heating above 4° C. is normal, and thereafter he volume of a given mass of water increases with increase in temperature. n this range water becomes less dense with increase in temperature. Thus, ater has its maximum density at 4° above the freezing temperature — g/cm^3. This anomalous behavior of water accounts for the nearly uni- orm temperature of 4° C. in the deep water of lakes when covered with ce during winter. Most of the water beneath the surface of the ice is ° warmer than the water in contact with the ice itself. The cooler ater next to the ice is less dense and floats on the warmer, denser ater beneath. This unusual behavior prevents lakes from freezing solid n winter, thus saving many forms of plant and aquatic life.

Addition of heat usually warms substances. The descriptive words hot," "warm," and "cold" are subjective terms. One of the empirical nventions made for the study of heat was that of the thermometer to neasure temperatures long before the nature of heat was understood.

We can regard temperature as the *intensity* of heat. A better explanation is that the temperature of a body determines whether it undergoes a net loss of heat energy to its surroundings. Thus, in Figure 232, the water in vessel *A* is at a higher temperature than the block of ice, since it progressively loses heat to the ice. In vessel *B* the water is at a lower temperature than the gas flame underneath since it is receiving heat from the flame. There can be no net flow of heat between objects at the same temperature. It should be noted that temperature is not dependent upon the amount of heat, but rather on its intensity or concentration. A gallon of water at room temperature contains much more heat as energy than a cup of water at the boiling point, though their temperatures are very different.

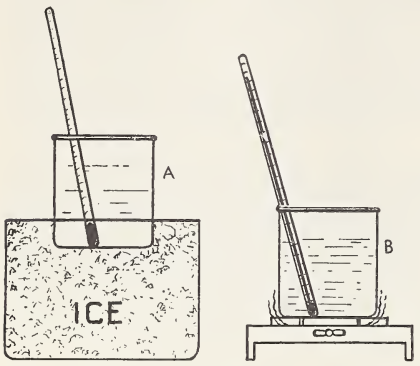


FIGURE 232. HEAT FLOWS FROM REGIONS OF HIGHER TEMPERATURE TO REGIONS OF LOWER TEMPERATURE

The two commonest forms of thermometer are the liquid-in-glass and the bimetallic-strip types, both based upon the differential expansion of unlike substances. The volume expansion of mercury is greater than that of glass. When it is subject to a temperature change, the mercury ex

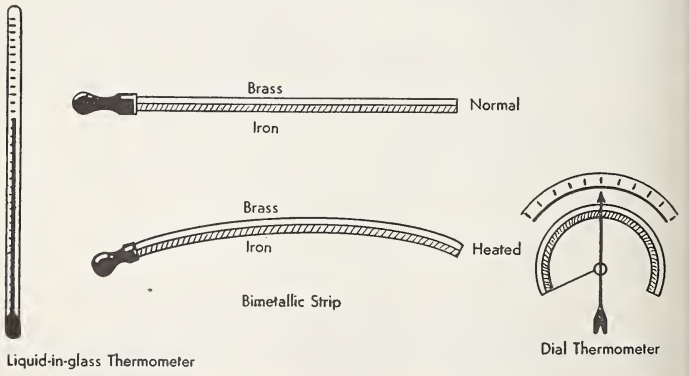


FIGURE 233. TWO TYPES OF THERMOMETERS
Liquid and bimetallic

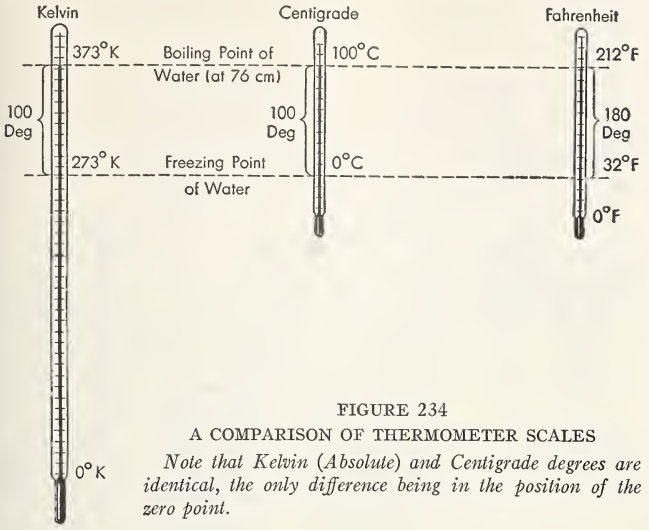


FIGURE 234
A COMPARISON OF THERMOMETER SCALES

Note that Kelvin (Absolute) and Centigrade degrees are identical, the only difference being in the position of the zero point.

ınds from the well into the column above. Suitable graduations indicate ıe extent of the change in temperature. Brass has a greater degree of :pansion than iron. If brass and iron strips are riveted together, the hole assembly will bend if subjected to a temperature change. The nount of bending is a function of the temperature change and can be dicated on a suitable scale. This is the principle involved in the com- on bimetallic-strip thermometers.

The "degrees" of temperature indicated by a thermometer are now :termined with reference to the freezing and boiling points of water, hich are fixed points. The position of the mercury column in a bath of elting ice and water is marked 0° on the Centigrade thermometer and ?° on the Fahrenheit. Similarly, the position of the mercury column in bath of live steam above water boiling under a pressure of one atmosphere marked 100° on the Centigrade and 212° on the Fahrenheit thermome- r.

Equal weights of different substances do not change like amounts of tem- :rature when they receive equal quantities of heat. A simple experiment ill suffice to bring out this truth. Two pieces of lead of mass two hundred ;ams each were placed in two hundred grams of water at 100° C. — the)iling point of water — until they were at the same temperature. One the blocks of lead was quickly transferred to two hundred grams of ycerine at 20° C., which increased in temperature to 24.5° C. — a change 4.5 degrees. The second block of lead was transferred to two hundred

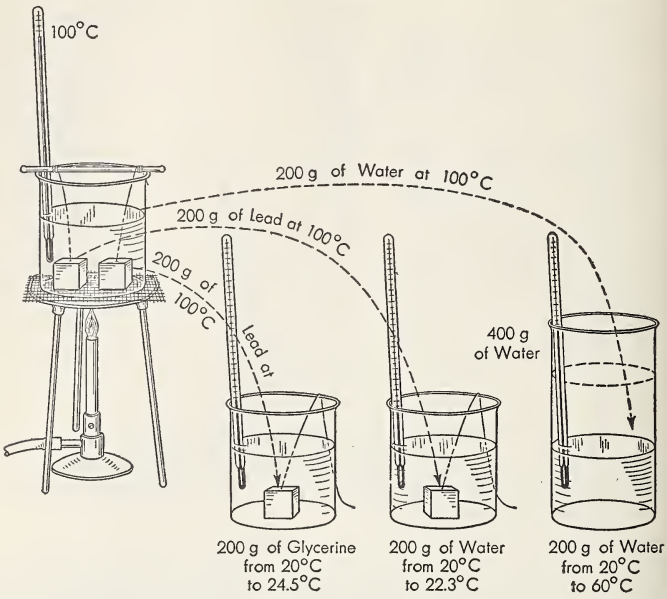


FIGURE 235. DIFFERENT SUBSTANCES HAVE DIFFERENT HEAT CAPACITIES

grams of water at 20° C., which was thus heated to 22.3° C. — a change of 2.3 degrees. The two hundred grams of water at 100° C. were then transferred to two hundred grams of water at 20° C., which was promptly heated to 60° C. — a rise of forty degrees. Two conclusions can be made.

(1) The water at 100° C. transferred much more heat than an equal mass of lead at the same temperature.

(2) A given quantity of heat will change the temperature of glycerin much more than an equal weight of water.

Similar experiments carried out with many other solids and liquids indicate that they differ enormously in the way they change in temperature when heated. Conversely, substances differ greatly in the quantities of heat given off when they are cooled. Furthermore, it is found that the quantity of heat needed to change the temperature of one gram of water one degree is greater than that needed for almost any other substance. Hence, it is convenient to use water as a reference standard in experiments dealing with the relation between heat and temperature. This is conveniently expressed in the concept of *specific heat*, the quantity of heat needed to raise the temperature of a given quantity of substance one degree in temperature as compared with the amount needed to change the temperature of an equal amount of water one degree.

TABLE 27. SPECIFIC HEAT OF SOME COMMON SUBSTANCES

Solids		Liquids		Gases	
ad	0.031	Water	1.00	Air	0.241
on	0.110	Glycerine	0.511	Nitrogen	0.240
anite	0.192	Mercury	0.033	Carbon Dioxide	0.202
uminum	0.210	Oil (paraffin)	0.510	Steam (At constant pressure)	0.465
salt	0.20				
ass	0.110–0.200				
e	0.530				

ne Common Heat Units

The high specific heat of water is the basis for the common units for easuring quantities of heat — the *calorie* and the *British thermal unit* or .T.U. The calorie is the quantity of heat necessary to change the temerature of one gram of water 1° C. The B.T.U. is the quantity of heat quired to change the temperature of one pound of water 1° F. The .T.U. is equal to 252 calories.

There are natural phenomena that can be explained on the basis of a owledge of specific heats. Thus, water because of high heat capacity a good carrier of heat and an excellent cooling agent. No other liquid ould serve as well for transferring heat in a hot-water system or in a hotater bottle, nor as a cooling medium in the radiator of an automobile. he relatively high freezing point of water, 0° C., is a disadvantage in the oling system of a car in winter. But the substitution of a liquid like erosene (specific heat 0.50) with a lower freezing point would be dangerus because of its inability to cool the engine properly.

The specific heat of rocks is about 0.20. This means that the hot rays the sun in the summer will heat the land adjacent to large bodies of ater to a much greater degree than the water. For the same reason large odies of water cool much more slowly than the adjacent land in the utumn and deliver up vast quantities of heat. Thus, all large bodies of ater profoundly affect the climate. Extremes of high and low temperaure are always found in the interior of the continents far from the oceans. emperatures as high as 110° F. during summer and as low as − 40° F. ave been reported from the plains of Montana.

The climate of certain large areas of the earth is characterized by definite ry and wet seasons. During summer the land is heated to much higher emperatures than the ocean, so that the prevailing winds are landward, ringing with them large quantities of water vapor which is precipitated s rain. During the winter season, dry winds from the interior of the contient blow oceanward, thus bringing on the dry season. The climates of ndia, Mexico, and Brazil have definite wet and dry seasons.

Heat is necessary to bring about changes in state of matter. It is not alays true that the addition of heat to matter results in an increase in emperature. If heat is added to a vessel containing ice water, a thermometer will show that it is impossible to raise the temperature above

0° C. as long as ice is present in the vessel. The change in state of ice int liquid water, or vice versa, takes place at a constant temperature, an experiment shows that a definite quantity of heat energy is involved. Th eighty calories needed to convert one gram of ice into water without chang in temperature is called the *heat of fusion* of ice. Note that, as pertains t the surroundings, fusion is a cooling process, while freezing is a heatin process.

$$1 \text{ g of ice at } 0^\circ \text{ C.} + 80 \text{ cals} \underset{\text{freezing}}{\overset{\text{melting}}{\rightleftharpoons}} 1 \text{ g of water at } 0^\circ \text{ C.}$$

After the ice in the experiment that has just been described is completel melted, the addition of heat will result in an increase in temperature unt a temperature of 100° C. is reached, at which point boiling occurs. A long as boiling continues, it is impossible to raise the temperature abov 100° C. The conversion of water liquid into water vapor or steam i likewise referred to as a change of state, and a definite number of calorie are absorbed per gram of steam formed, namely, 540 calories. This i referred to as the *heat of vaporization.*

To summarize, the conversion of a pure solid into a liquid and the proces of boiling take place at definite temperatures, referred to as the meltin point and the boiling point. These changes of state involve definit amounts of heat energy.

Work can be performed with heat. This point will not be elaborate upon at this time, except to mention that the steam engine and the in ternal combustion engine are fundamentally machines for converting hea into motion or kinetic energy.

Heat is produced by three principal processes. These processes are th combustion of such fuels as wood, coal, oil, and gas; surfaces rubbin against each other — friction; and the passage of electricity through a co ductor, as in the use of an electric toaster or flatiron. It is always true tha energy used to overcome friction appears as heat. Electric motors, fo example, if not properly oiled will often run so hot that the bearings a ruined and must be replaced. (Refer to page 358.)

The Nature of Heat Energy: The Caloric Theory

The problem of the nature of heat puzzled scientists and philosophe from the time of Pythagoras, who held that matter was composed of earth water, air, and fire. But the nature of fire was so little understood tha small progress was made in explaining heat phenomena until the advent o the caloric theory, so named by Joseph Black (1728–1799), a famou Scottish scientist. According to this theory, heat is a "subtle, invisibl weightless fluid, passing between the particles of bodies with perfect fre dom." In the light of present knowledge, to postulate the existence of "weightless fluid" is not reasonable. Nevertheless, the caloric theor

ıd a great vogue and it was remarkably successful in explaining many the facts concerning heat. The caloric theory, for example, made it ɔssible to measure heat changes quantitatively. Thus, Black devised ethods of calorimetry, invented heat units, and experimentally measured ɔecific heats and heats of fusion and evaporation, with the guidance of ıe caloric theory.

But troublesome facts kept bobbing up which the caloric theory could ɔt account for. Sir Humphry Davy in 1799 melted ice merely by rubbing ⁄o pieces together, even though the ice was below the freezing point of ıter. The significance of this experiment was in bringing about melting ithout the addition of heat as such. About the same time, Benjamin ıompson (later Count Rumford) was impressed by the amount of heat ⁄olved during the boring of cannon. Rumford was born in Massachusetts, ıt at the time of the Revolution left for Europe, where he moved in gov- nmental and intellectual circles both in England and on the Continent. e is remembered for his contributions to the science of heat, for adapting e advances of science to the social advancement of mankind, for found- g the Royal Institute in London, and for endowing the Rumford Pro- ssorship in Harvard University.

Rumford became convinced that work against friction results in heat, ıt he had to combat the advocates of the caloric theory. In one experi- ent, Rumford succeeded in bringing water to the boiling point with heat oduced in the boring of cannon, and the boiling continued as long as ring continued. Rumford argued that it was unreasonable that inherent loric could come from the brass of the cannon continuously. To believe at heat inherent in matter could be extracted continuously and still leave e matter in its original condition was as unreasonable, according to ımford, as to believe that water could be squeezed from a sponge con- ıuously without loss of weight. In this operation, Rumford insisted, e heat came not from the brass, but from the work expended on the ring operation. According to the calorists, caloric was liberated during e boring operation. Very well, then, countered Rumford, the borings ould differ from the original brass by having a lower specific heat. He und no difference in the specific heat of the metal before and after boring.

Rumford's final conclusion was definite but rather difficult to under- and: *Heat is motion.* In the boring experiments, the power was furnished ⁄ horses, and the heat was really produced by the work of the horses and timately by the oxidation of the fodder consumed by the horses. Rum- rd undoubtedly had a clear picture in his own mind of the fact that heat ıs energy, though his picture of heat as motion needed fifty years or so r final clarification.

ıe Equivalence of Heat and Work

The epoch-making experiments of James Prescott Joule, announced in ngland in 1847, finally proved to a skeptical scientific world the equiva-

lence of energy and heat. In effect, Joule sought to determine the exper mental value of the proportionality constant, J, needed to transform th relationship,

$$W(\text{ork}) \propto H(\text{eat}),$$

into a mathematical equality, namely,

$$W = JH, \text{ or } J = \frac{W}{H}.$$

This constant is known as the *mechanical equivalent of heat.* The essential parts of the best-known apparatus used by Joule to determine the value of J are indicated in Figure 236. The vessel A contains a known mass m of water. In this vessel the paddle wheels rotate against the friction of the water by placing a known mass M on one of the pans, say P_2. When the mass has fallen to the floor, it is transferred to the other pan, P_1, which i the meantime has been raised a distance equal to that through which P has fallen. The mass M will again fall to the floor. This operation ca be repeated as many times (n) as desired. In this way a definite, measu able amount of work is performed against friction, with the result that known amount of heat is produced:

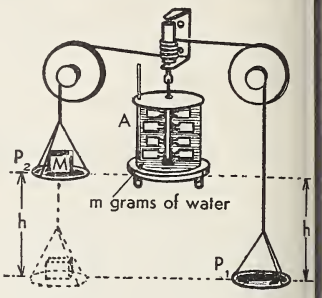


FIGURE 236. JOULE'S METHO FOR DETERMINING THE ME CHANICAL EQUIVALENT OF HEA

$$\text{Work performed} = W = nMgh \text{ ergs}$$
$$\text{Heat produced} = H = m\,(S)\,(t_2 - t_1)$$

In the last expression, S = specific heat of water = 1 calorie per gra per degree Centigrade, $(t_2 - t_1)$ = rise in temperature of the water. Joule many experiments showed that work may be converted into heat and tha there is always a definite relationship between these two quantities; tha is, a definite amount of work is equivalent to a certain amount of heat.

$$J = 4.18 \times 10^7 \text{ ergs of work to produce 1 calorie, and}$$
$$1 \text{ B.T.U.} = 25030 \text{ foot-poundals of work.}$$

This quantity is referred to as the *mechanical equivalent of heat.*

Conservation of Energy

The results of Joule's work played a very important part in establishin the principle of *Conservation of Energy*, or the *First Law of Thermody namics*. This is one of the most basic, universal, and useful laws in scienc A concise statement follows: *Energy can neither be created nor destroyed; can only be transformed.* A re-reading of the discussion on machines o pages 352 to 359 will take on added significance in terms of this law. I is this law, for example, which precludes the possibility of perpetua motion, or work without expenditure of energy.

The Kinetic Theory

Another of the great generalizations of science representing a synthesis from many fields of knowledge and using facts and principles that accumulated principally during the period 1750 to 1850 is the *kinetic theory.* Many of the various phenomena and principles previously mentioned in connection with heat were discovered or studied as more or less isolated phenomena. The many attempts to account for all these phenomena with one comprehensive theory were not successful until the evolution of the kinetic theory. The story of this theory superbly illustrates the function of a tentative hypothesis to explain the whys and wherefores of observed facts and scientific inductions or laws.

Contributing ideas for the final elucidation of the nature of heat came from many different sources and individuals. As has been pointed out before, Rumford suggested the idea that heat is motion; the reality of the atom and molecule as tiny particles of matter was inferred from the researches of Lavoisier, Dalton, Avogadro, and others. Joule's experiments established the fact that heat is a form of energy and can be neither created nor destroyed, although it may be modified as to form. The stage was set for derivation of the hypothesis that the particles — molecules — of matter are in continuous motion, and that, therefore, the individual molecules of a gas must possess kinetic energy. A given volume of gas according to this conception, then, contains energy as heat, which is the sum of the kinetic energies of the individual molecules, or,

$$\textit{Heat content of a gas} = n\left(\tfrac{1}{2}\, mv^2\right),^{1}$$

where n represents the number of molecules, m their mass, and v their average velocity. (Refer to page 349.) Heating alone will not change the number of molecules, nor their mass. Hence, if a sample of gas is heated, the heat content must increase because the kinetic energy of the molecules increases. This means, therefore, that the kinetic energy of the molecules changes because of an increase in the average velocity of the molecules.

Consider a toy balloon filled with hydrogen gas floating in air. The balloon is tightly distended, because of the impacts of rapidly moving molecules on the sides of the balloon as they hit and rebound an inconceivably large number of times each second. A bullet from a gun will give only an isolated "push" on a target if the gun is fired only occasionally. But a continuous stream of bullets from a rapidly fired machine gun would exert a continuous push on the target. Rapidly colliding molecules on the walls of the balloon exert a similar effect.

[1] Lack of space precludes a full discussion of all aspects of the energy of molecules, a part of which is translational, a part vibrational, and a part rotational. This treatment is limited to a molecule which has only translational energy which can be altered by heat, as in the case of helium. Students interested in a more complete discussion of this topic should refer to an advanced treatise on the kinetic theory of gases.

At the time the kinetic hypothesis was invented, the reality of a molecule could not be demonstrated. The scientist could only assume the existence of molecules of hydrogen endowed with random motion. These molecules were supposed to be very numerous and separated from each other by distances which were enormous compared with their own size. They had one unusual property; they lost no energy when they collided and rebounded. The random motions of an excited swarm of bees in a closed box is a visible counterpart of the motions of the molecules of a gas in a vessel. Some of the bees will fly into the walls and exert an outward push, just as the molecules of hydrogen in the toy balloon exert pressure. But many of the bees will be injured by the collisions against the walls and drop to the floor of the box. Furthermore, the bees will eventually tire and stop flying. Nothing like this happens, however, to the molecules; they never tire in their ceaseless motions, and the innumerable collisions with the walls and with each other do not affect their velocity. This is one kind of perpetual motion which is not a delusion. The property which is responsible for rebound of molecules from a wall with no loss in energy or velocity is *elasticity*. Molecules are assumed to be perfectly elastic.

In scientific thinking, hypotheses must be checked against all known facts. The kinetic theory readily accounts for the various heat phenomena already mentioned in this chapter. We have seen how collisions of molecules cause pressure. If a gas is heated, the molecules move faster. Thus the kinetic energy of the molecules — the heat content and temperature — increases. Therefore, the molecules will collide with walls more frequently and with greater force. The consequence is an increase in pressure. The autoist who drives too long and too fast on a warm day may have a blowout from the increased pressure within the tire as it gets hot. Heating a gas, therefore, increases the pressure exerted by the gas and accounts for its tendency to expand.

The distances between the molecules of a gas are large as compared with the size of the individual molecules. This accounts for the fact that gases are easily compressible. For example, a gram of water at room temperature has a volume of about one milliliter. But a gram of steam at 100° C. occupies 1700 ml. The volume of the voids between the molecules of steam must then be at least 1699 ml. The fact that gases are easily compressible is readily explained on the basis of reducing the volume between molecules as the applied pressure is increased.

Any process that will decrease the frequency of impacts or the magnitude of the individual push of impact on the walls of the container will reduce the pressure exerted by the gas. This can be done by (1) increasing the volume of the gas, or by (2) decreasing the temperature. Thus the impacts of the molecules in vessel *A* in Figure 237 cause a pressure of one atmosphere which is indicated upon an ordinary pressure gauge. If the piston is then withdrawn until there is an indicated volume of two liters

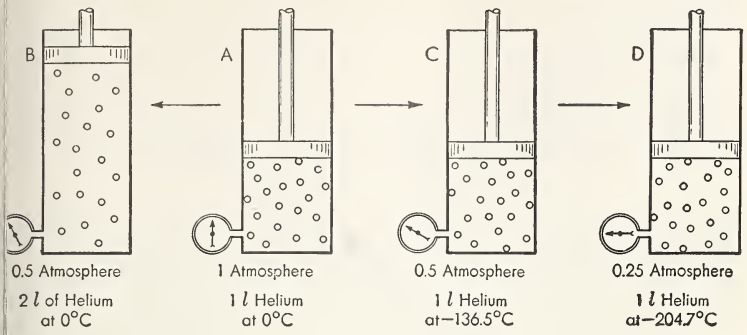


FIGURE 237. PRESSURE EXERTED BY SAMPLE OF GAS CHANGES WITH VOLUME OR TEMPERATURE

ıe frequency of collision will be reduced one-half. The gauge read- g falls to 0.5 atmosphere. If instead of increasing the volume occu- ed by the helium, the temperature is lowered, there must be a removal heat energy. The molecules then have lower individual velocities and ıe frequency of collision and the force of individual impacts will both be duced. This means reduced gaseous pressure. Experiment shows that the temperature is reduced to − 136.5° C., the pressure becomes 0.5 mosphere, while a reduction in temperature to − 204.7° C. decreases ıe pressure to 0.25 atmosphere.

Actual experiment indicates that the pressure exerted by a gas continues decrease in a regular manner with a decrease in temperature. Table 28 ıows how the pressure exerted by a sample of helium decreases with the mperature. The data are plotted in Figure 238.

TABLE 28. PRESSURE OF HELIUM AT LOW TEMPERATURES

olume	Temperature Centigrade=$t°$	Pressure in atmospheres	Temperature absolute $T°$
1 l	0°	1	273.0
1 l	− 136.5	0.5	136.5
1 l	− 204.7	0.25	68.3
1 l	− 225	0.17	48.0
1 l	− 250	0.084	23.0

The relation between pressure and temperature is more apparent from he graph in Figure 238. Note that the graph is a straight line, and that the temperature were sufficiently lowered, the pressure would eventually ecome zero. The process of extending a curve into a region where no xperimental data exist is known as *extrapolation*. The extrapolated part f the graph in Figure 238 is indicated by the dotted line. Note that it ıtercepts the x-axis at − 273° C. This temperature has a tremendous

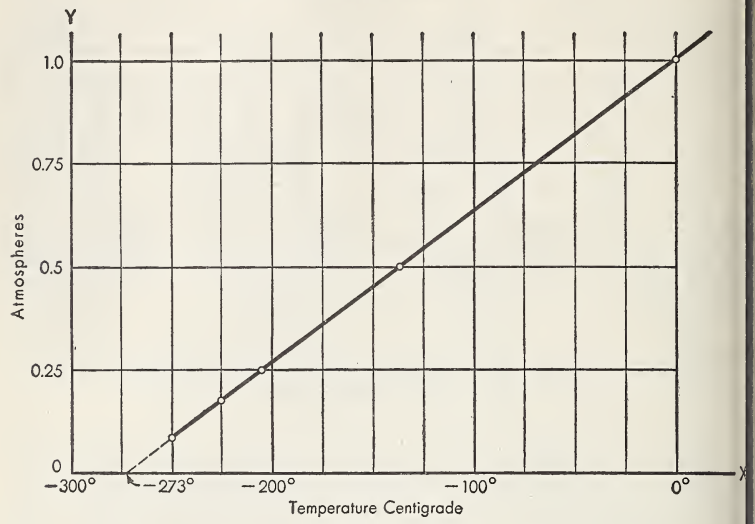


FIGURE 238. A DECREASE IN TEMPERATURE LOWERS THE KINETIC ENERGY OF MOLECULES

significance in scientific thought. It represents the ultimate in coldness the absolute lack of heat energy — the temperature at which the molecule of all substances are without motion. It is known as the *absolute zero.*

In discussing the meaning of temperature on page 367, it was shown tha the Fahrenheit and Centigrade temperature scales were the result of em pirical invention. One consequence of the discovery of the absolute zer of temperature was the evolution of a logical temperature scale, the abso lute or Kelvin temperature scale, in which,

(*T*)emperature absolute = (*t*)emperature Centigrade + 273.

The temperatures in the fourth column in Table 28 are in the absolute scal

Absolute zero is a temperature that scientists have approached ver closely, but never hope to reach. From an experimental point of view it is entirely imaginary. There are many factors which make experimen tation in the vicinity of absolute zero a matter of special techniques i heat measurement. For example, no liquid-in-glass thermometer woul function, since the liquid would have frozen long before absolute zero wa even approached. In spite of the enormous difficulties, it is interesting t note that physicists have actually reached temperatures less than a hun dredth of one degree above absolute zero.

The absolute temperature of a gas is directly proportional to the hea content or the kinetic energy of all the molecules. (Refer again to Tabl

8 and notice that the changes in the data in the last two columns parallel ach other; that is, the pressure is directly proportional to the absolute emperature.) The kinetic energy of n molecules is $n(\frac{1}{2}mv^2)$. It is en- irely impractical to determine n and v for every sample of gas. Nor is t necessary, for a more convenient measure of the kinetic energy of the nolecules or heat energy of a gas is its absolute temperature T. That is,

$$\textit{Heat content} \propto n\,(\tfrac{1}{2}\,mv^2) \propto T.$$

Thus far, our discussion of matter has been limited to the gaseous state. ny gas can be liquefied by increasing the external pressure and reducing he temperature. In liquids, the molecules are in very close proximity to ach other and the voids between them are small compared with the voids etween the molecules of a gas. Refer to page 374 for the volume of one ram of steam compared to a gram of liquid water. However, the mole- ules of a liquid still undergo random motion, though lacking the freedom hey have in the gaseous condition. It is this motion that accounts for he tendency of liquids to evaporate. A moving molecule possesses nomentum (mv) and there is continual exchange of momenta between the nolecules in the liquid as they collide with each other. The result is that ome molecules have velocities considerably greater than that of the aver- ge. It is these faster-moving molecules that occasionally leave the liquid nd pass into the space above to form a vapor. Since the slower molecules emaining in the liquid possess less energy, the temperature of the liquid alls. The process of evaporation is hastened by the application of heat. Hence, evaporation is a *cooling process*. A person wet with perspiration vill often suffer a chill if exposed to a breeze. The air passing over the ody hastens evaporation, and the heat necessary for the evaporation omes from the body itself. Rapid removal of heat from the body is esponsible for the chill.

Evaporation usually occurs at the surface of a liquid, but in boiling, evap- ration also occurs within the liquid itself to form the bubbles of steam haracteristic of boiling. This is called *ebullition*. The temperature at vhich water boils is dependent upon the pressure of the atmosphere. In

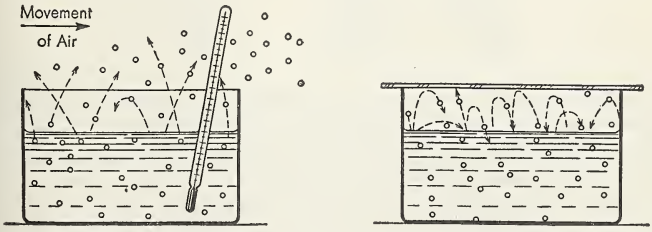


FIGURE 239. WHY DOES A LIQUID EVAPORATE IN AN OPEN VESSEL?

boiling, steam issues from the vessel. To boil a liquid, it is necessary to supply enough energy to the molecules to enable them to push the molecules of air out of the vessel. Hence, the pressure exerted by the vapor from the liquid must be equal to the pressure of the surrounding air. Furthermore, the bubbles which form at the bottom of boiling water can consist of steam alone, and they get larger as they move up through the liquid itself. A bubble just beneath the liquid surface cannot exist unless the pressure within the bubble, P_B, is equal to the pressure of the air, P_{air}, on the surface of the liquid. (Refer to Figure 240.) Hence, a decrease in atmospheric pressure means that bubble formation can occur at lower temperatures, and vice versa. This is shown in Table 29.

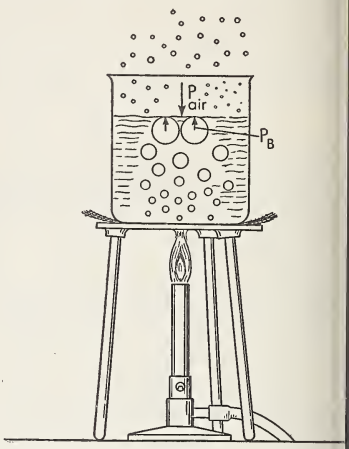


FIGURE 240. CONDITIONS NECESSARY FOR BOILING

A boiling liquid does not mean a high temperature. Thus, water boils at 100° C. when the pressure is one atmosphere, but at 46° C. if the pressure is 0.10 atmosphere. Liquid helium boils at − 268.9° C. when the pressure is one atmosphere. Mercury, on the other hand, boils at 356.9° C.

TABLE 29. PRESSURE OF WATER AT VARIOUS TEMPERATURES

t° C.	Pressure mm of mercury	Pressure in atmospheres
0°	4.60	0.0065
20°	17.50	0.023
50°	92.5	0.13
75°	289.1	0.38
100°	760.0	1.0
120.4°	1520.0	2.0
200°	11659.0	15.3
300°	64432.0	84.7

A "three-minute egg" prepared on the top of Pike's Peak would have to be in boiling water about 8.5 minutes. At the altitude of Pike's Peak, fourteen thousand feet, the barometric pressure is about 455 mm. of mercury, and the corresponding boiling point of water about 86° C. The preparation of canned food is an important industry. To save time in the cooking of the food and to insure sterilization, canned foods are invariably prepared under high pressures. A household pressure cooker operates

under a gauge reading of fifteen pounds per square inch (two atmospheres) will be operating at a temperature of 120° C. Food which requires an hour for preparation in an open kettle will require only fifteen minutes in a pressure cooker.

The transition of a liquid to a solid also evolves heat energy. Anyone who has examined a snowflake, the frost on a window, or a crystal of salt or sugar, even under a low-power magnifying glass, will be impressed by the beautiful crystal structures. Refer to page 45 (in Chapter 3) for some illustrations of typical crystalline substances. All solids are characterized by a definite, orderly geometric arrangement of the units which enter into the formation of the crystal — molecules, atoms, or ions. However, the molecules in a crystal still possess energy, so the individual molecules have a certain amount of motion. The mean positions about which the molecules hover within the crystal do not change with respect to each other.

There are various forces of attraction between the molecules within a crystal which account for its rigidity. A solid does not melt until enough heat is supplied to the individual molecules to overcome the forces of attraction. As we have seen, the energy needed to melt a solid is called the heat of fusion, and the same quantity of heat is evolved when the solid is formed from the liquid — amounting to eighty calories per gram in the case of water.

In discussing the kinetic theory, we have spoken of very small particles, called molecules, of exceedingly minute mass moving at very high velocities. Modern science has successfully answered the questions: How small, how heavy, and how fast? Information about molecules, obtained deductively by a mathematical treatment of the kinetic theory in connection with certain experimental data, is given in Table 30.

Table 30. Characteristics of the Molecules in Air

Number in 1 ml	2.70×10^{19}
Average velocity	about $\frac{1}{3}$ mile per second
Molecular diameters	2×10^{-8} cm
Collisions per second	5×10^{9} per second
Mean free path: Average distance traveled between collisions	1×10^{-5} cm

Transference of Heat

Conduction is the carrying of heat from one locality to another by molecular action. In conduction of heat through a solid, for example, the enhanced molecular motion resulting from supplying heat is progressively transferred from molecule to molecule by collision. Thus, heat is transferred through the solid with no transfer of the solid itself. This means that heat travels by conduction from regions of high temperature to regions of low temperature. Different substances differ widely in their

ability to conduct heat. Metals as a class are excellent conductors. Substances with little ability to conduct heat are referred to as heat insulators.

The quantity of heat that passes through any barrier depends upon at least five variables:

1. The area of the conducting surface — the larger the area, the greater the quantity of heat transmitted. In Figure 241 for example, an area of two square feet would transmit twice as much heat as one of one square foot.

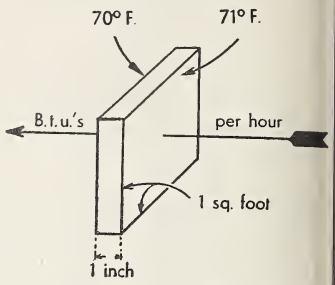


FIGURE 241. TRANSFERENCE OF HEAT

2. The thickness of the conducting surface; that is, a conductor two inches thick would transmit half as much heat as one inch of the same material. This is an inverse relationship.

3. The difference in temperature between the two sides — the greater the temperature difference, the greater the quantity of heat transmitted.

4. The time — the quantity of heat transmitted will vary directly as the time. This means that five times as much heat will pass through in five minutes as in one minute.

5. The nature of the material itself. Thus a sheet of cork of same dimensions as a piece of iron will transmit less heat than the iron. In Chapter 3, there was a discussion of the use of the symbolism of mathematics to summarize the results of experiments. This procedure is especially helpful when there are many variable factors as in the conduction of heat. All the facts given above can be stated symbolically,

$$\begin{aligned} H(\text{eat}) &\propto A(\text{rea}) \\ &\propto \text{temperature difference, } (t_2 - t_1) \\ &\propto T(\text{ime}) \\ &\propto \frac{1}{L(\text{ength})} \end{aligned}$$

Therefore,

$$H = \frac{KA\,(t_2 - t_1)\,(T)}{L}$$

This single equation contains every fact given in the long paragraph that just preceded it. The proportionality constant K in this expression is called the *coefficient of thermal conductivity.*

The coefficients of thermal conductivity of some common substances are tabulated in Table 31. Silver, the best conductor, is nearly seven thousand times as good a heat conductor as corkboard. When you go skating, your hands may successively touch the skate runner, the wooden park bench, and a woolen mitten. Subjectively it seems as though the skate is colder than the wood, and the wood, in turn, seems colder than the

TABLE 31. HEAT CONDUCTIVITY OF SOME COMMON SUBSTANCES

	K*	Relative Conductivity (Silver = 1)	Relative Insulating Ability (Corkboard = 1)
lver	1715	1.00	0.00017
)pper	1615	0.94	0.00018
uminum	888	0.52	0.00028
)n	284	0.17	0.00088
ranite	20	0.012	0.013
ater	2.52	0.0015	0.099
sbestos paper	1.08	0.00062	0.24
ood (pine)	0.98	0.00057	0.25
wdust	0.41	0.00024	0.61
:lotex	0.34	0.00020	0.74
)ck wool	0.26	0.000152	0.98
)rkboard	0.25	0.000146	1.00

Good Conductors ↑ ↓ Good Insulators

* K = B.T.U.'s transmitted per hour through a thickness of one inch and an area of 1 square foot for a temperature difference of one degree Fahrenheit.

itten. In reality, they are probably at substantially the same tempera- re. The apparent difference in temperature is due to conduction of eat away from the hands. The iron skate, being the best conductor of e three, removes heat from the hand faster and seems coldest.

There are many situations where the choice of a material to be used as a nductor of heat will depend upon its ability to conduct heat. Thus, the diator shell of an automobile, designed to cool the circulating water, is ually made of copper. Aluminum is superior to iron or enamel for aking cooking-ware because it is a better heat conductor by a factor of ree. Similarly, there are many situations where the choice of a material ll depend upon its ability to function as a heat insulator. The best in- lators are usually light and porous materials containing as little solid aterial as possible and having many small "dead air" spaces. Re- gerators, ovens, and furnaces are usually insulated, either to keep heat or to keep it out. The best insulator is a vacuum. A good approxi- ation to a perfect insulator is the ordinary silvered vacuum flask, popu- r for keeping liquids either cold or hot. The purpose of the silvered rface will be discussed in a later chapter on radiation. (Refer to page 3.)

The tendency in recent years to install "automatic heat" in homes has lled attention to the money-saving qualities of good insulators. Com- etely automatic heat requires relatively expensive fuels — oil or gas — that their use in most homes without insulation would be prohibitive.

A second important process for the transference of heat is that of *con- tion.* This is the process that is prominent in the transference of heat rough liquids and gases. It does not occur in solids.

Reference has been made to the expansion, upon heating, of liquids d gases. As a result of the expansion, a gas becomes less dense than the

surrounding air and is lifted upward by the denser, cooler air. This set up an actual movement of air which results in a transference of heat. I conduction, heat is transferred through matter with no visible movemen of the medium itself. In convection, matter moves and carries heat with it A striking visible demonstration of the process of convection is the upwar spiraling of smoke from a glowing cigarette. The circulation of warm ai or hot water in home-heating systems is an analogous process. The wind and ocean currents represent convection currents on a huge scale.

The effectiveness of many insulating materials, such as corkboard an rock wool, depends upon two things: First, they are composed of substance which are very poor conductors of heat; and secondly, they are porous with the tiny voids filled with air. Hence, these materials prevent loss o heat by convection.

There is a third important process for transference of heat: *radiation* Energy transferred by this process is called *radiant energy*. Heat energ is conducted through matter by conduction, is transferred with and o matter by convection. But in the transference of radiant energy, matte is not involved, for radiant energy travels as invisible waves with th velocity of light. Further discussion of this topic will be postponed t Chapter 44, where wave motion and the electromagnetic spectrum will b studied.

SUMMARY

1. Heat is the form of energy which is involved in many chemical changes an in the operation of all forms of heat engines.
2. Any theory of the nature of heat must be able to explain common phenomen which involve heat, such as: (*a*) matter with few exceptions increases i length and volume when heated; (*b*) addition of heat to substances usuall results in an increase in temperature; (*c*) substances differ enormously in th way they change in temperature when supplied with heat; (*d*) heat is neces sary to bring about changes in state; (*e*) work can be performed with hea
3. The kinetic theory successfully accounts for all the various phenomena whic accompany the addition or withdrawal of heat from a substance.
4. Substances which can lose heat energy to their surroundings at a rate greate than the rate at which they receive heat have a higher temperature tha the surroundings.
5. The common temperature scales are the Fahrenheit, Centigrade, and abs lute.
6. The common heat units for measuring quantity of heat are the calorie an the B.T.U. One B.T.U. = 252 calories.
7. The ratio of the quantity of heat needed to change the temperature of a sub stance one degree compared with the quantity needed to change the tempe ature of an equal quantity of water one degree is known as specific heat.

8. The number of calories needed to melt one gram of a solid without change in temperature is called its heat of fusion. For ice this is eighty calories.

9. The number of calories needed to change one gram of a liquid to vapor without change in temperature is known as its heat of evaporation. For water at 100° C., this is 540 calories.

0. James Prescott Joule established the equivalence of heat and work, establishing the important principle of Conservation of Energy, or the First Law of Thermodynamics.

$$J = 4.18 \times 10^7 \text{ ergs} = 4.18 \text{ joules} = 1 \text{ calorie, and}$$
$$1 \text{ B.T.U.} = 25030 \text{ foot-poundals}$$

1. Heat transfer occurs by three processes, (*a*) conduction, (*b*) convection, and (*c*) radiation.

2. The kinetic theory is largely responsible for our present understanding of the three physical states of matter. The theory readily accounts for such phenomena or facts as the following:

(*a*) The pressure exerted by gases and their tendency to expand is due to rapidly moving, perfectly elastic molecules.

(*b*) Gases are markedly reduced in volume by an increase in external pressure because of the relatively large space between the molecules.

(*c*) Heat as energy is the kinetic energy of rapidly moving molecules.

(*d*) The change in the heat energy of a substance is due to a change in the speed and thus the kinetic energy of the molecules.

(*e*) At the absolute zero of temperature, the molecules of a substance are stationary and the heat energy is zero.

(*f*) The heat content of a substance is directly proportional to its absolute temperature.

(*g*) A sample of liquid substance possesses definite volume, but its molecules still possess relatively great freedom of movement.

(*h*) A true solid consists of molecules in a crystal in positions relatively fixed with respect to each other but still possessing some vibratory motions about mean positions.

. The process of evaporation requires an absorption of heat and results in cooling the surroundings. The converse is true in condensation.

. The process of melting requires an absorption of heat and likewise results in cooling the surroundings. Heat is evolved in freezing.

STUDY EXERCISES

. Below you will find certain definitions or statements pertaining to material presented in this chapter. Associate by number the correct response from those listed at the right with each definition or statement.

.. The scientist who devised the absolute temperature scale.

.. The temperature at which a substance possesses no energy in the form of heat, i.e., there is an absence of molecular motion.

1. Calorie
2. Convection
3. Joule
4. Kelvin

.... The process of heat transfer where heat energy passes through a substance from molecule to molecule.
.... The quantity of heat necessary to change the temperature of unit mass of a substance one degree in temperature.
.... The investigator who did much to disprove the caloric theory of heat.
.... The process of transferring heat which is employed in warm air heating systems.
.... The quantity of heat in calories needed to melt one gram of ice without change in temperature.
.... The quantity of heat needed to change the temperature of one pound of water one degree Fahrenheit.
.... The quantity of heat in calories needed to convert one gram of water at 100° C. into steam without change in temperature.
.... The quantity of heat needed to melt one gram of a substance at its melting point without change in temperature.
.... The scientist who gave convincing experimental evidence for the equivalence of work and heat.

5. Conduction
6. Count Rumford
7. Heat of fusion
8. Specific heat
9. 540 Cals/g
10. B.T.U.
11. 80 Cals/g
12. Heat of evaporatio
13. Absolute zero
14. Helmholtz

2. Use the kinetic molecular hypothesis to explain the following phenomena:
   (*a*) If a bottle of ammonia water is left unstoppered, the odor of ammonia soon apparent through the room.
   (*b*) A rubber balloon inflated with hydrogen soon collapses.
   (*c*) There are often alternate dark and light streaks on the plaster ceilings heated rooms.
   (*d*) A vessel of water, if allowed to evaporate spontaneously, is lowered temperature.
   (*e*) A person moist with perspiration is often "chilled" if he stands in breeze.
   (*f*) Why does dust tend to move from the warmer to the cooler part of room?
   (*g*) If water is placed on a layer of syrup in a vessel, the two layers gradual "mix."
   (*h*) A certain vessel held one pound of air at a pressure of one atmospher When an additional pound of air was pumped into the same vessel, t pressure became two atmospheres.
   (*i*) A toy balloon filled with air was found to expand in volume when plac in the light of the noonday sun.
3. Encircle correct answers:
   (*a*) What quantity of heat is needed to change the temperature of one gra of water from 15° to 16° C.?
   1000 Cals 1 Cal 50 Cals 500 Cals
   (*b*) How many calories are needed to change 50 g of water from 15° C. 16° C.?
   1000 Cals 1 Cal 50 Cals 500 Cals

(*c*) How many calories are needed to change 50 g of water from 15° C. to 35° C.? *1000 Cals 1 Cal 50 Cals 500 Cals*

4. While playing a game of basketball you lose 400 ml water by evaporation. Heat of evaporation of water is 540 cal/g.
   (*a*) How many calories of heat were lost by your body?
   (*b*) If all this heat was due to playing basketball, how many ergs of work did you do? (1 Cal. = 4.18×10^7 ergs)
   (*c*) A player during the course of a hard basketball game often loses from three to five pounds in body weight. Account for this loss in two ways.
5. Hot water suddenly poured into a thick drinking glass will often cause a crack. Explain.
6. One wall of a room 100 square feet in area was made of one inch pine. A similar wall of the same room was made of one inch corkboard. If the interior temperature was 72° F. and the exterior 32° F., by suitable calculations make a comparison of the heat lost through each wall. Consult Table 31, page 381, for necessary data.
   Encircle correct answers:
   (*a*) The number of B.T.U.'s lost through one square foot of pine wood per hour for a temperature difference of one degree Fahrenheit is
   94,080 0.98 0.25 24,000
   (*b*) The number of B.T.U.'s lost through 100 square feet of pine wood for a temperature difference of forty degrees Fahrenheit per day is
   94,080 0.98 0.25 24,000
   (*c*) The number of B.T.U.'s lost through 1 square foot of corkboard per hour for a temperature difference of one degree F. is
   94,080 0.98 0.25 24,000
   (*d*) The number of B.T.U.'s lost through 100 square feet of corkboard per day for a temperature difference of 40° F. is
   94,080 0.98 0.25 24,000

FOR FURTHER READING

1. Lemon, H. B., *From Galileo to the Nuclear Age.*
   Chapters 14, 15, and 16 discuss the results of adding heat to matter and the meaning and measurement of temperature. Chapter 17 takes up heat capacity and the methods used to measure heat quantities. Chapter 18 contains an interesting presentation of the kinetic theory as an outstanding example of a successful scientific theory. The student should try to read all these chapters.
2. Harrison, George R., *Atoms in Action.* New York: William Morrow and Company, 1941.
   Chapter I, "The Taming of Energy," discusses the meaning of energy and some recent developments in developing and transporting energy.

21

Heat Engines: The Power of Modern Civilization

IN ONE OF THE GREAT STORIES of antiquity, a young hero, about to di
exclaims: "Lo, I have borne my burden . . .!" To most modern you
people these words sound strange, for life appears to be anything but
burden. They little realize that today we are resting on the achievemen
of the past and that, although life is perhaps easy and the home sce
pleasant, it has not always been so; even today there are many millions
people in the world to whom the burden of life has a very significant mea
ing. It means that children work; that the soil is not particularly ferti
There are storms and droughts that must be considered. There are i
sects competing for man's food. There are no "gas-propelled" plow
hardened human hands supply the power to earn a subsistence out of t
soil. It is not an uncommon sight to see a man or woman bearing t
burden of the beast — wood for the fire. It has been pointed out th
through inventiveness man has been able to change and modify his e
vironment to suit his advantage. These changes have not only made t
task of obtaining food, shelter, and protection easier, but have also e
tended the abilities of man. We are accustomed to machines, and witho
their use not even a fifth of the present population could subsist on t
earth. The modern machine enables man to do work at a rate undream
of by even the enlightened ancients. The excavation for the foundation
the Colosseum in Rome was performed by many men working for month
The same task could be accomplished today by the steam shovel in
fraction of the time. The rate of doing work, or *power*, is the foundati
of modern industrial civilization.

The energy supplied by the human body was sufficient for the work th
had to be done among very primitive people. When the farmer su
planted the hunter, the moving of large masses to build huts and the plo
ing of the earth involved hard and fatiguing work. Consequently, d
mestication of animals appeared simultaneously with the use of bett
tools and agriculture by Neolithic man. The horse, camel, and ox wo

useful to early man for motive power and meat supply. From tools to simple machines is not a great jump in the evolution of ideas; machines multiply the force of muscular power, requiring at the same time less skill than the use of tools. The wheel was probably suggested by the rolling log used to transport heavy objects. From this early discovery have sprung all the later adaptations — water wheels, chariot wheels, windmills, and the wheels of modern industry — as man acquired new sources of power. But from the earliest records of the Egyptian and Babylonian civilizations down to the last century, kingdoms and empires moved with beast power and slave power. The freight trains were camels and horses; when beast power was not sufficient, slaves were used. Even the Athenian democracy rested on slavery, and if Lincoln had proclaimed his ideas in Athens, he would have met the same fate as Socrates, to whom the Athenians gave hemlock for a lesser offense. Slavery did not disappear from civilized nations until the inventions of the nineteenth century provided far cheaper motive power than that of all the slaves and domesticated beasts in the world. The steam engine was invented between 1750 and 1800, and the steamboat between 1801 and 1803; the power loom in 1813; the locomotive between 1825 and 1827; the sewing machine in 1829; the electric motor in 1837. Inventions of labor-saving devices increased tremendously during the nineteenth century, and after thousands of years of effort the quest for power to lift man's burden began to be rewarded. The development of heat engines permitted the use of such fuels as coal and oil for the production of heat and the conversion to mechanical energy; that is, it "put fuels to work." Great economic changes followed. The railroad and the steamboat not only increased commerce and led to greater industrial specialization, but facilitated the settling of new frontiers, particularly in this country. Enormous industries developed and created large population centers, primarily because of steam power and the application of cumulative scientific knowledge.

Principle of Heat Engines

The operation of all heat engines involves the transformation of the chemical energy of fuel into heat and the conversion of part of this heat into work. Since heat represents the kinetic energy of the molecules, when a fuel burns, the temperature of the air-fuel mixture rises, and therefore the kinetic energy of the molecules, or their velocity of motion, increases. In starting a car, the mixture of air and gasoline just before it is sprayed into the cylinder of the automobile has the same temperature as the air which the driver breathes. When the mixture ignites within the cylinder, the temperature rises to nearly 2000° C. (3600° F.). This means that the molecules within the cylinder are in violent random motion. The molecules push the piston and are thereby slowed down, part of their kinetic energy being transferred to the moving piston and flywheel which

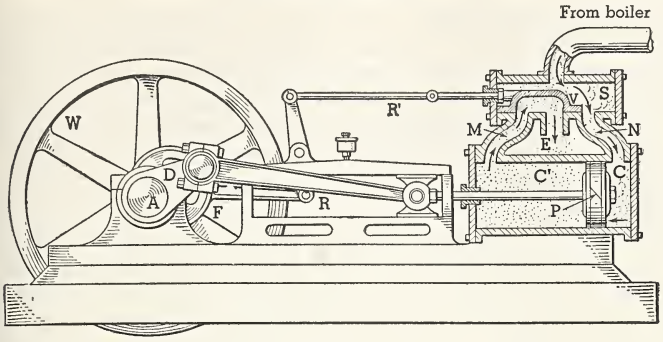
do work. It should be pointed out that the change of heat energy in mechanical energy involves a change of the random motion of the mol cules into motion with direction, while the reverse process — the chan of mechanical work, or energy, into heat — involves the change of directe motion into random motion of the molecules. A definite amount of m chanical energy can be completely changed into heat, but only part of definite amount of heat can be changed into mechanical energy or wor In order to convert all heat into work, it would be necessary to change th random motion of all molecules into the directed motion of a piston or fly wheel without any loss; stated in another manner, the change would in volve the transfer of the entire kinetic energy of the molecules to the pist or flywheel, and thereby reduce the motion of the molecules to nothing, the temperature to absolute zero — a condition which cannot be attain in practice.

The operation of a locomotive or of any other steam engine is the sam namely, the change of part of a given amount of heat into work. Coal oil is burned under a boiler containing water. The combustion involv a chemical change during which heat is liberated. The molecules of th products of combustion are heated to a temperature of 1200° to 1500° and therefore are in a state of rapid motion. Part of this motion is tran ferred by metallic conduction to the water within the boiler. The wat boils, producing gaseous water molecules, or steam. Since the steam is n allowed to escape, the temperature and pressure rise. This steam is l into the steam box where the molecules in violent motion knock against piston and push it, thus losing some of their kinetic energy and being slow down. In other words, the exhaust steam from a locomotive and the e haust gases from the automobiles are at a lower temperature than bef they pushed the piston. It follows from this consideration that in or to obtain work from a heat engine we must start at a higher temperatu and come down to a lower temperature.

The Modern Steam Engine

The steam engine is called an *external combustion* engine, since the h is produced under a boiler and then conducted to water, changing it steam. The steam is transferred into the engine proper, where it is allow to expand and move a piston. The gasoline engine is of the *internal co bustion* type; the fuel-air mixture is fired within the engine and the gases are allowed to expand, moving the piston.

In the steam engine, the fuel — usually coal or oil — is burned benea a boiler, which usually consists of metallic tubes filled with water, leadi into a drum above. As the fire and smoke heat the tubes, steam is g erated and fills the drum. In order to have a hot fire, a forced draft o tall chimney provides a rapid air supply. The steam is heated abo 100° C. and consequently is under pressure, which varies between ten a



IGURE 242. SECTIONAL VIEW OF A SIMPLE RECIPROCATING STEAM ENGINE

irty atmospheres (150 to 450 pounds per square inch), corresponding to mperatures of 180° and 234° C., respectively. The super-heated steam nters the steam box which is marked by S in the diagram shown in igure 242. The steam passes into the cylinder through the opening N, ver which is a sliding valve V. As the superheated steam enters the ylinder space C, it pushes the piston towards the other end of the cylinder '. The motion of the piston P is communicated through the connecting od R and crank D to the shaft A, which is provided with a heavy fly-heel W. When the piston has been pushed about one-fourth or one-ird of the length, the sliding valve V is moved by the eccentric F and the ccentric rod R', and the inlet of steam to the space C is cut off. From his point on the steam expands, or increases in volume, pushing the piston ward the other end of the cylinder. The expansion of steam is accom-anied by a drop in its temperature; in other words, the molecules are owed down by imparting a portion of their momentum to the piston. s the piston moves toward the left end of the cylinder, the steam that ay be left in the space C' is forced through the opening M into the ex-aust pipe E. Just before the end of the stroke the sliding valve admits team through the opening M into the space C' and connects N to E to ermit the expanded steam in C to escape. The steam admitted in space ' forces the piston back to the right. Thus steam is alternately ad-itted at each end, is allowed to expand, and then exhausted, moving the iston and connecting rod back and forth. Hence the engine is known as he reciprocating type. The crank changes the straight-line motion of he piston into the circular motion of the shaft. The heavy flywheel is sed in order to maintain a uniform motion.

pplication of Kinetic Theory to Steam Engine

The common steam engine is an example of a machine for converting

heat into mechanical energy. The efficiency of this process can be deduce with the kinetic theory. Consider a simple reciprocating steam engine a shown in Figure 242. Steam enters the engine from a boiler under hig pressure, say 30 atmospheres, when it is at a temperature of 509° $K(T_1$ The average velocity of the molecules is about 1800 mi/hr. Molecules steam lose a part of their energy on each impact against the piston. I other words, the kinetic energy lost by each molecule per collision appea as kinetic energy in the moving piston. This follows from the *first law thermodynamics*. The total energy imparted to the piston depends course upon the total number of molecules in the cylinder (n), and th total number of collisions during one passage of cylinder by the piston At the end of the stroke, the spent steam is allowed to escape to a condens or to the atmosphere. If the steam is exhausted to the air at a pressu of one atmosphere, it will leave the steam cylinder at a temperature 373° K, which is T_2. As the steam imparted energy to the moving pisto it was cooled, but the molecules were still moving about 710 mi/hr. L E_1 and E_2 represent the energy of n molecules of steam as it entered a left the cylinder, and u_1 and u_2 the respective molecular velocities. Th we can write,

$$\text{Energy entering steam} = E_1 = n\left(\tfrac{1}{2}\, mu_1^2\right) = nk\, T_1 \qquad (1)$$

This follows since heat energy is merely the kinetic energy of molecul and the amount of this kinetic energy is directly proportional to t absolute temperature. (Refer to page 378.) Similarly,

$$\text{Energy exhaust steam} = E_2 = n\left(\tfrac{1}{2}\, mu_2^2\right) = nk\, T_2 \qquad (2)$$

Hence the heat transformed into mechanical energy is given by

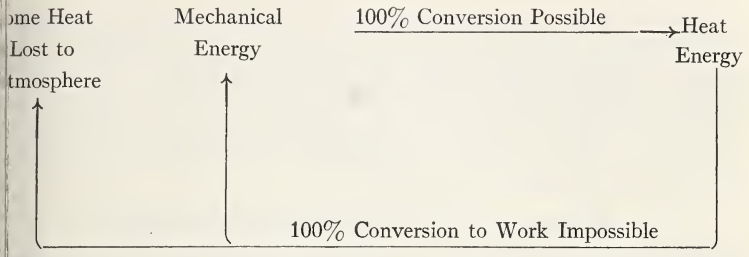
$$E_1 - E_2 = nk\, T_1 - nk\, T_2 = nk\,(T_1 - T_2)$$

and the fraction of the energy transformed is

$$\frac{E_1 - E_2}{E_1} = \frac{nk\,(T_1 - T_2)}{nk\, T_1} = \frac{T_1 - T_2}{T_1} \qquad (3)$$

The conclusions represented by Equations (1) and (2) merit further exam nation. Equation (2) indicates that the efficiency of the ordinary stea engine must always be relatively low since such a large fraction of t original energy of the steam (E_2/E_1) must always go out the exhaust unavailable energy. In the example given above, the unavailable ener amounts to $nk\, T_2/nk\, T_1$, or 373/509 = 74 per cent. This means that the above steam engine, even if perfect with no losses due to friction, on about one-fourth of the energy of the entering steam is actually convert into work.

Equations (2) and (3) have another important implication, namely, hat it is *never possible to convert heat energy entirely into work* in a heat ngine operating in ordinary surroundings. The reverse process, the con- ersion of a given amount of work entirely into heat, however, is possible. hese two important conclusions can be diagramed as follows:



The equation, $\frac{E_1 - E_2}{E_1} = \frac{T_1 - T_2}{T_1}$,

a statement for the *second law of thermodynamics*. This law, with the st law, is literally the basis for the whole science of energetics — the udy of energy. The whole sequence of the development of more efficient at engines is based upon the application of these two laws.

leasurement of Power

Power has been broadly defined as the rate of doing work. Work was fined as the product of force times distance. In using the term power ie element of time is added: *power* means the time rate of doing work.

$$P(\text{ower}) = \frac{W(\text{ork})}{t(\text{ime})} = \frac{F(\text{orce}) \times D(\text{istance})}{t(\text{ime})}$$

The common unit by which power is measured is called a *horsepower*. his is defined as the rate of doing 17,700 foot-poundals of work per second. he origin of this unit is connected with the early use of steam engines to mp water from coal mines. The work up to that time had been done y horses on treadmills. Therefore the power of the steam engines was pressed as equal to the work done by so many horses. Watt, who made ie most conspicuous improvements on the steam engine, determined by number of experiments the amount of work that a horse could do in a ven time. He found, for example, that a strong draft horse, by means a rope and pulley, pulled a weight of a hundred and fifty pounds from a pth of slightly more than two hundred and twenty-one feet in one inute. Hence, the work done in one second by the horse was:

$$\text{Work done} = F \times D = mgh \text{ (see page 348)}$$
$$= 150 \times 32.174 \text{ ft/sec}^2 \times 220 \text{ ft}$$
$$= 1{,}062{,}000 \text{ lbs-ft}^2/\text{sec}^2$$
$$= 1{,}062{,}000 \text{ foot-poundals.}$$
$$\text{Work done in one second} = \frac{1{,}062{,}000}{60} = 17{,}700 \text{ foot-poundals.}$$

An example will serve to illustrate the meaning of the term horsepowe Assume that a young man weighing one hundred and sixty-five poun runs up a flight of stairs twenty feet high in ten seconds. It is obvio that the man does work to lift his body against the force of gravity for distance of twenty feet; since we can calculate the amount of work he d and we know the time that it required him to do this work, we can calcula the horsepower which he developed:

$$\text{Work done} = 165 \times 32 \times 20 = 105{,}600 \text{ foot-poundals.}$$

As this work was done in ten seconds, the man did 10,560 foot-pounda of work per second. Since one horsepower is 17,700 foot-poundals of wo per second, the power developed by the man in running up the flight stairs is $10{,}560/17{,}700 = 0.6$ horsepower.

Automobile engines develop from fifty to one hundred and fifty horsepowe Locomotives vary between five hundred and two thousand horsepowe airplane engines vary from one hundred to two thousand horsepowe The power developed by some airplanes is more than one horsepower p pound of weight, which is remarkable. Steam turbines have been bui which are capable of two hundred thousand horsepower or more.

The Steam Turbine

The steam turbine is more efficient than the reciprocating engine because it permits greater expansion of steam, occupies less space, and runs without much vibration. The turbine consists of a drumlike shaft, or *rotor*, inside a casing carrying a number of rotating disks or wheels with blades or buckets attached to the rims (Figure 243), and between each pair of wheels is a set of stationary blades or guide vanes attached to the casing or nozzles. Steam enters the turbine at one end and, passing through a set of nozzles, impinges upon the stationary blades (guide vanes), by which it is directed against the movable blades (buckets) of the wheel or rotor, where it expands and is directed by

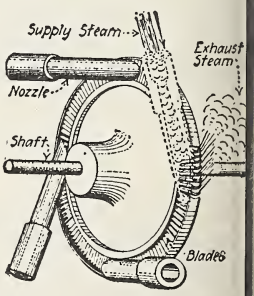


FIGURE 243. THE PRINCIPL OF THE STEAM TURBINE

A turbine wheel with blad and a set of nozzles. Steam fr the phantom nozzle may be se impinging upon a number blades. (Courtesy of De La Steam Turbine Co.)

nother set of stationary blades against the blades of the next wheel, and
› on. In this manner the steam expands in stages in the multiple-expan-
on type of turbine; the pressure and temperature drop, while the volume
ıcreases. A turbine so constructed increases in diameter in the direction
: the exhaust end. Large turbines, which may develop as much as two
ındred thousand horsepower, have an efficiency of 30 to 40 per cent and
:e used as marine engines and electric generators.

Small turbines are also coming into use for driving blower, compressor,
ıd centrifugal pumping units, or any type of machinery that can be driven
om a rotating shaft, and are available in sizes from one horsepower up to
ıree thousand horsepower. Since they run at high speed, a large amount
: power is developed by a small engine.

ıe Development of the Steam Engine

The development of the steam engine, like most discoveries, has been a
ries of improvements by several persons. The properties of hot air and
eam were known to the ancients. Hero, of Alexandria, a Greek mathe-
atician and writer on mechanical subjects who lived A.D. 50–100, records
his books several contrivances which indicate clearly such knowledge.
ı his books are found such modern "inventions" as slot machines, auto-
atic organs, war engines, siphons, fire extinguishers, and contrivances
nploying the force of steam. Hero's steam turbine is shown in Figure
4. Water was heated in the lower vessel, where it generated steam which
ıssed through the hollow supports into the globe. Escape of the steam
om bent tubes facing tangentially in opposite directions caused the globe
› revolve on the reaction principle (Newton's Third Law). No further
ttention was paid to Hero's records until the rediscovery of classical
ience in the seventeenth century, when Giovanni della Porta, Leonardo
ı Vinci, and others redirected attention to the properties of hot gases.
homas Savery, in 1689, used steam successfully to raise water out of coal
ines, and Newcomen, a few years later, introduced the first cylinder-and-
ston engine.

In the Newcomen engine, shown in Figure 245, steam was admitted
om the boiler to the cylinder and the piston was raised by a counter-
eight. When the piston reached the top of the cylinder, the steam valve
as shut and a jet of cold water sprayed into the cylinder, condensing the
eam and thereby producing a vacuum. The piston consequently was
›rced down by the pressure of the atmosphere; this was the power stroke.
he next entry of steam expelled the condensed water from the cylinder
ıd started the cycle again. The Newcomen engine was used for pumping
ater out of coal mines. The next improvement afforded a tremendous
ıpulse to the use of steam engines. It came some sixty years later, when
ames Watt, an instrument-maker at the University of Glasgow, repaired
Newcomen engine. Watt was impressed by the large waste of steam in

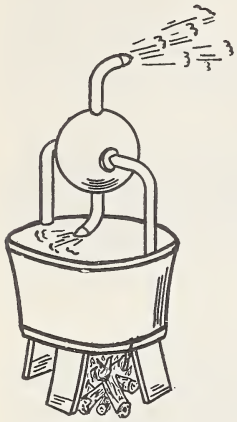


FIGURE 244
HERO'S ENGINE

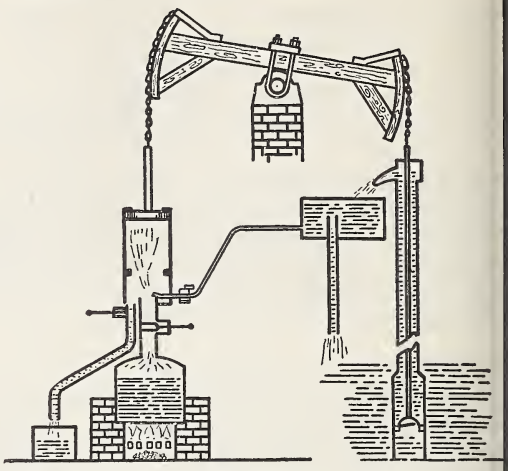


FIGURE 245
NEWCOMEN'S ENGINE

the engine due to the alternate heating and cooling of the cylinder; ov 85 per cent of the steam entering the steam box was utilized in reheati the cylinder wall from the temperature of the previous condensation, a only about 12 to 13 per cent of the steam was utilized in doing work. Watt added a condenser into which the steam from the cylinder escap and in which it was then condensed. This striking improvement led the modern steam engine.

It should be noted that this development was made after the use of co for quickly producing large amounts of heat became general. In oth words, heat engines would not have been developed if fuels had not be available. The Watt engine ushered in the industrial revolution. T next improvements were the reciprocating engine and the use of steam higher pressures. The steam turbine was developed in the last decad of the nineteenth century. However, the scientific basis for improveme of heat engines had been thoroughly investigated since 1820 by Sa Carnot, a brilliant young French artillery officer who died at the age thirty-six. Carnot established the principles which govern the maximu motive power obtainable from any quantity of heat and worked o mathematical expressions for the efficiency of the heat engine which w discussed in the preceding section. On the basis of his studies he point out the way to improve heat engines. When coal is burned under t boiler, the temperature is 1200° to 2000° C., but by the time the steam ente the cylinder the temperature is only around 150° to 200°, which represen a large loss of heat. This is unavoidable in any engine which uses vap

a medium of heat transfer. Therefore, reasoned Carnot, the only way avoid this loss is to burn the fuel inside the cylinder; thus he pointed t the way for the development of the internal combustion engine. Fifty ars elapsed before this suggestion was applied in practice. The gasoline gine was developed between 1862 and 1876. The modern automobile, ctor, and airplane use internal combustion engines.

e Gasoline Engine

The essential parts of a gasoline engine are the following: (1) An ex-sion chamber having on the top a spark plug and containing a cylinder th a sliding piston, the spark plug being connected to an electrical timing vice which sends a spark across the gap of the spark points at proper ervals. (2) Inlet and outlet valves in the explosion chamber to permit e fuel to come in and the gases, after combustion, to pass into the ex-ust pipe. There is one inlet and one outlet valve for each cylinder.) A carburetor which provides a regulated mixture of gasoline and air be introduced into the explosion chamber. The carburetor connects rough a pipe line with the gasoline tank. (4) A system of pistons and nnecting-rods attached to a crank shaft which changes the up and down tion of the piston to the circular motion of the flywheel. (5) Finally, a ling and lubricating system. The cylinder of the gasoline engine sup-es the place of the furnace, boiler, and cylinder of the steam engine. e temperature is raised to nearly 1300° C., and it would not operate g if it were not cooled from the outside. It is usually cooled by being rrounded with a jacket in which water circulates. The water from the ket is forced into the radiator for cooling. Airplane air-cooled engines ve the outer surface of the cylinder corrugated, thus exposing greater face, and are cooled by a stream of air forced over this surface.

The Four-Stroke Cycle. In order to understand the operation of the gas-ne engine we will consider the operation of the automobile engine when it ut into operation by "stepping on the starter." (Refer to Figure 246 ich resolves the operation into four movements of the piston, twice up-rd and twice downward.) The piston *P* moves within the cylinder *C* and connected to the crank shaft *D* by means of the connecting rod *A*. The nk shaft *D* is connected to a heavy flywheel not shown in the figure. e engine is started by turning the shaft *D* by means of the starter which a small motor operated by a battery. On the first stroke the piston ves downward, the inlet valve *I* opens, and the fuel charge of gasoline ay and air is drawn from the carburetor; then the inlet valve closes. is is the *intake* stroke. Since it is assumed that the engine is cold, the mperature is between 60° and 90° F., and the pressure is one atmosphere, fifteen pounds per square inch. As the motion continues, the piston ves upward with both valves closed, and the charge is compressed to m one-fourth to one-seventh of its original volume. The usual compres-

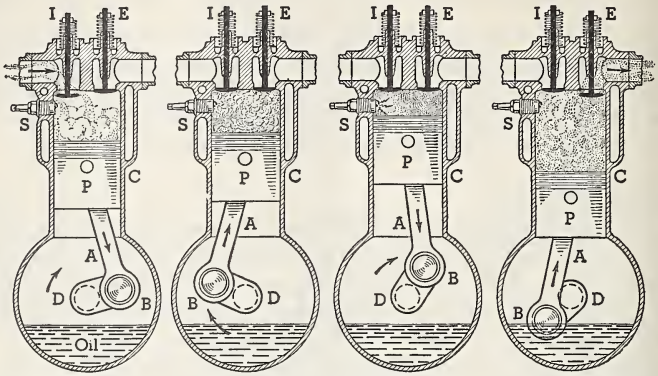


FIGURE 246 FIGURE 247 FIGURE 248 FIGURE 249

sion ratio is 1:6, and therefore the pressure within the cylinder rises to s atmospheres. Compression heats the gasoline-air mixture to about 550° This stroke is called the *compression* stroke and is shown in Figure 24 As soon as the piston reaches the top of the cylinder, as shown in Figu 248, the contact-breaker geared to the shaft transmits a spark across t gap of the spark-plug points, and a rapid combustion of the gasoline-a mixture takes place. The temperature rises to about 3000° F., and the pr sure to about twenty-five atmospheres (four hundred pounds per squa inch), and consequently the piston is pushed down by the expanding h gases. This is the *expansion* or *power* stroke. The motion is transmitt through the crank to the flywheel. After the piston has reached the botto and begins to rise again, the outlet valve *E* opens, and the combustion ga are forced out (as shown in Figure 249) through the muffler and exha pipe into the atmosphere. This is the *exhaust* stroke, and it completes t cycle, for the next downward movement of the piston begins the same cy again — *intake, compression, firing and expansion,* and *exhaust.* This cy requires two complete revolutions of the crank shaft for its completi Since power is obtained only on every fourth stroke, the heavy flywheel used to keep the engine going, and more than one cylinder is used. T average automobile has six cylinders, although four, eight, nine, twelve, sixteen cylinders are used in some automobile and airplane engines. T firing in the cylinders is so adjusted that some one of the cylinders is deliv ing power at each successive firing.

The theoretical efficiency of the gasoline engine is in the neighborho of 38 per cent, but the actual efficiency is only about 25 per cent. T foregoing discussion indicates that the efficiency of the gasoline engi depends on the ratio of compression. For example, if the compressi ratio is 1:4, the power obtained will be about twice as great as when t

io is 1:2. Therefore the compression of the charge should be made as h as possible. There are limiting factors, however, that prevent raising compression ratio very high. It was pointed out in preceding paraphs that as the gasoline-air mixture is compressed the temperature s. With a compression ratio of 1:6, the temperature rises (in a cold inder) to nearly 550° F., and therefore as the compression increases the nperature rises to such a point that ignition takes place before the timer ds the spark into the cylinder. Another disadvantage of very high npressions is that the combustion of the gasoline-air mixture proceeds re like an explosive detonation, which causes the engine to "knock." e troublesome pre-ignition as the compression is raised suggested the a of the Diesel engine.

Diesel Engine

The Diesel engine resembles the gasoline engine; it differs from it in t it has no electrical devices or carburetor, but a valve for injecting the l.

At the intake stroke, the Diesel engine draws in air; at the compression oke the air is compressed to from one-sixteenth to one-twentieth of its ginal volume. The pressure rises upwards of five hundred pounds per are inch and the temperature to 1000° F., which is nearly the temperae of dull red-hot iron. When the piston reaches the top of the cylinder, fuel is injected through a valve operated by a small pump and burns mediately. The pressure may rise to eight hundred pounds per square h, and expansion of the hot gases produces the power stroke as in the oline engine. The fourth stroke is also similar to the gasoline engine hat the gases are expelled. Since the fuel does not have to be easily porized, kerosene or fuel oil may be used instead of gasoline. The higher npression enables the Diesel engine to give greater power than the gaso- e engine at every stroke, and therefore it has a higher efficiency; in t, it is one of the most efficient heat engines. The Diesel engine is vy and is particularly adapted for marine and locomotive engines. cord speeds of one hundred and twenty miles per hour by streamlined ins using Diesel engines have been established. Recently, models Diesel engines have been constructed to operate trucks and tanks, l they have been experimentally designed for automobiles. The effincy of the Diesel engine is high at part load as well as at full load, ereas the gas engine drops off very greatly in efficiency when operated at mall part of its rated capacity. The Diesel engine is primarily a connt-speed engine, and to adapt it to any particular type of work, means uld be provided so that the engine can operate at practically a constant ed while allowing the vehicle to operate at whatever speed may be essary.

Airplane Engines

The engines used in aircraft are essentially the same as automob engines, built, however, to meet special requirements. The essential quirements are light weight, extreme reliability, high efficiency, and l frontal area.

The first two requirements work at cross ends; it would not be diffic to build sturdy engines, provided they were to be made of heavy met Therefore, light alloys must be used and all parts carefully fabricat Whereas the failure of an automobile engine is rarely of any consequen the failure of an airplane engine usually leads to disaster. Hence ev precaution is taken to test the reliability of the engine. Two spark pl are installed in each cylinder and the engine must be run for many ho at full throttle before approval. To eliminate weight, air-cooled engi are preferred to water-cooled. More recently, ethylene glycol, an orga liquid of high boiling point, has been used to advantage for cooling plane engines. In order to be cooled by air, the cylinders are arran radially around the crank case, and nine cylinders are the most that ca crowded around it; this, however, increases the frontal area. Airpl engines are being built now with the cylinders in line, V-shaped, or dou banked radially. It is thus possible to increase the power, which is especial requirement of the airplane.

One of the essential differences between the automobile engine and airplane engine is the mode of operation. The automobile engine is sta and then slipped into low gear; after the automobile is moving, the sp is increased, but it is usually run at less than half speed and rarely at throttle. The airplane engine is at full throttle during the take-off climb, and at three quarters for the remainder of the flight. The airpl propeller must operate at maximum or nearly maximum speed in o to change the torque power of the engine into forward thrust. Conne with these requirements of high efficiency is the problem of selection of airplane fuel. The engine must run with a low fuel consumption deliver the maximum amount of power; hence special grades of gas are used, as discussed in Chapter 34.

The Reaction Engine (Jet Propulsion)

Under the stress of World War II tremendous advances were mad the development of a new type of heat engine commonly called *jet pro sion engine* but more correctly designated as the reaction engine. E work on this type of engine was done by Goddard in the United St and by Opel in Germany where most of the rapid development took p during the last two years of the war. The basic principle of the opera

all reaction type engines is Newton's third law of motion (see page 229). nsider, for example, an engine of mass M from which hot gases of mass are discharged with a high velocity V from one end of the engine; then ording to the third law,

$$mV = Mv,$$

ich indicates that the discharge of gases with a high velocity from one l of the engine is accompanied by the motion of the engine of mass M the opposite direction with a velocity of v. It is important to know t the motion does not depend upon air or any substance for the dis- rging gases to "kick" against, but on the fact that as a consequence of third law the gases discharging in one direction produce a motion on engine in the opposite direction.

Reaction engines are considered the most efficient engines thus far eloped, for they give a conversion of heat energy to work from 50 to per cent.

There are two types of reaction engines. The first, called the *rocket* e, operates without air; it carries liquid or solid fuel (usually alcohol) its own oxygen for combustion (usually in the form of 80–90 per cent drogen peroxide). Because there is no dependence on air for the oxygen ply needed in the combustion of the fuel, this type of engine can rate high above the earth's air layer. The "V-2" rocket is of this eral type.

The second kind of reaction engine, called the *jet engine*, is being adapted present to airplanes. Like the Diesel, it draws large quantities of air ch is compressed and utilized in the combustion of the fuel, usually ie low-grade oil. But whereas in the Diesel the gases are utilized to ve pistons, in the jet they are discharged from one end of the engine h a high velocity, thus imparting motion to the engine in the opposite ction.

rigeration

The heat engines considered thus far involve the transfer of heat from a to a cold region. In the steam engine, for example, water is changed heat to steam, which is then transferred into a cylinder, where it gives some of its heat and is condensed back to water; the latter may be re- ned to the boiler and recycled. The reverse of this cycle forms the basis efrigeration. A liquid which boils at a low temperature, usually below freezing point of water, serves as the medium to transfer heat from a l region to a hot region. The liquid is permitted to enter a cooling mber, where it abstracts heat from the surroundings, boils, and passes

into the vapor state. The vapor is pumped through a compression pu into a condenser, where it is changed into a liquid, giving off heat to t condenser; heat from the condenser escapes to the surrounding air outs of the refrigerator. The liquid is then returned to the cooling chamber be recycled.

The essentials of the electric household refrigerator are shown diagra matically in Figure 250. The medium of heat transfer may be sul dioxide, or methyl chloride, or dichlorodifluoromethane (Freon); all these substances boil far below the freezing point of water, and theref require pressure to be changed into the liquid state at ordinary tempe tures. The compressor, as shown in the diagram, is operated by an elect motor; it should be noted that electricity has nothing to do with the frigeration except to operate the compressor. The compressor is direc connected to the cooling unit, so that the refrigerant vapor is always low pressure. The refrigerant vapor is withdrawn by the compressor a

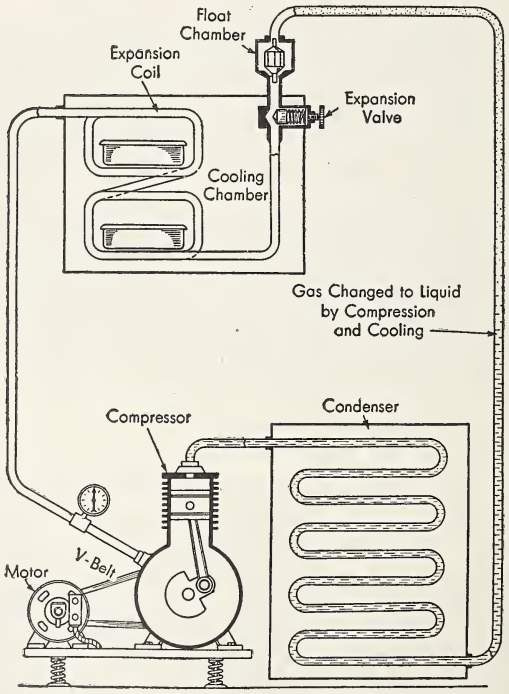


FIGURE 250. DIAGRAM OF A HOUSEHOLD MECHANICAL (COMPRESSION TYPE) REFRIGERATOR

pressed to from two to three atmospheres of pressure, and then passed he coiled condenser. The vapor on compression becomes heated, and molecules are brought closer together; since heat in the condenser is rapidly, the vapor liquefies and the liquid ascends to the float chamber the top of the cooling unit. The function of the float chamber is to ect the liquid refrigerant from the condenser and to regulate its flow the cooling unit. When sufficient liquid is collected in the float mber, the float bulb is lifted, opening a needle valve and allowing the uid to return to the cooling unit, at the top of the upper storage section he cabinet. The liquid refrigerant in the cooling unit evaporates when pressure on it is reduced by the suction from the compressor. In so porating, heat from the cabinet air and from water contained in the trays is absorbed through the cooling unit. Thus refrigeration is ained. In large refrigerators, which are used for cold-storage rooms l for manufacturing ice, ammonia is commonly used as the refrigerant dium. The process is not different from that described above. In the nufacture of ice, the cooling coils are immersed in large tanks of brine. ssels of pure water left suspended in the brine are frozen solid and are n withdrawn.

ial Effects of Heat Engines

his topic was discussed in a general way in the introduction to this pter. It will be well, however, at this point, to consider in more specific ail the social consequences of the introduction of heat engines. The of civilized nations has been completely revolutionized. The popula- n has increased over 500 per cent. England in Shakespeare's time l a population of 5,000,000; it doubled within fifty years after the intro- tion of Watt's steam engine, and is 45,000,000 today. Similarly, the ulation of Europe rose from 100,000,000 to 535,000,000. The age of veling peddlers, of the individual shops of smiths, shoemakers, and isans, where work was brought to the worker, gave way by degrees to modern scene of huge stores and factories where men congregate to do ir work. The age when every family raised most of its food gave way degrees to the present scene in which a very large proportion of families not even acquainted with the conditions under which food is raised processed.

The modern machine age appears on the whole humane, but its early ges of development were marked by inhumanity and exploitation of th adults and children, and bore the stamp of barbarism. Huge and leous towns sprang up overnight whose populations toiled drearily from ldhood to old age under the inexorable discipline of the factory whistle. at engines made vast amounts of power available. Production in- ased and made possible the accumulation of fortunes on a scale never herto dreamed of. Distances were minimized, cities became larger,

and governments more powerful. Labor-saving devices and inventio multiplied rapidly, so that within a century and a half the use of leisu time became a problem in some of the more industrialized communities.

Although the heat engine has solved a great number of problems f mankind, it has at the same time confronted the average individual with number of new problems. Life has become more complex, so that ma people have wondered whether the heat engine, instead of being a deliver has not enslaved a large proportion of mankind, and whether it does n threaten the destruction of civilization. Machines are blamed for d priving men of work and for wholesale destruction from the air. Manki has lost the security of a feudalistic society too rapidly and has been push forward at such a speed that it has been difficult to acquire new roo Growth has been so rapid, advance so swift, and new social problems vast that many of them still await solution. It is not the machine, ho ever, that is to be blamed, but the inability of man to apply to his soc problems the same method of thinking through which the machine w developed.

SUMMARY

1. Power is the time-rate of doing work.
2. In heat engines part of the heat produced in the combustion of a fuel is c verted into mechanical energy and performs work.
3. The steam engine and the steam turbine are external combustion engin Steam, generated outside of the engine, is allowed to expand, thus tra ferring some of its kinetic energy to the moving parts of the engine.
4. The automobile, airplane, and Diesel engine are internal combustion gines. The fuel is burned within the engine, and the compressed gases wh are produced expand to move the pistons.
5. Mechanical energy can be wholly converted to heat, but it is impossible convert heat wholly into work. The fraction of heat converted into w depends on the magnitude of the difference between the two temperatures which a heat engine operates.
6. The principle of refrigeration is the reverse of the cycle of a steam engine refrigeration a liquid which boils at a low temperature serves as the medi to transfer heat from a cold region to a hot region.
7. Man is consciously seeking sources of power. The development of heat gines has produced profound social effects.

STUDY EXERCISES

1. Explain in terms of the kinetic molecular theory the transformation of chemical energy contained in coal to the work obtained from the operatio a steam engine, in which the coal is utilized as a fuel.
2. Assume that you have sufficient coal which, when burned, will give you

million calories of heat. Of this heat, how much will be converted to work using a modern efficient steam engine? Enumerate all the losses and show which ones can be eliminated.

In the example above, assuming that we could eliminate all the losses of heat, could we ever obtain a 100 per cent conversion?

Below are listed a series of changes. Place after each change a plus (+) if during the change the velocity of the molecules in the system is increased; place a minus (−) if there is a decrease in the velocity of the molecules; place a zero if there is no change in the velocity of the molecules.

(*a*) Escape of air from an inflated tire.
(*b*) Compression of gasoline-air mixture in the explosion chamber of an automobile.
(*c*) Passage of the refrigerant contained in a household refrigerator to the coils of the freezer chamber where ice-cubes are made.
(*d*) Compression of the refrigerant in the above example from the freezer coils to the reservoir tank.
(*e*) Gases during the power-stroke of the automobile engine.
(*f*) Passage of air from one room to another while both rooms are at the same temperature.
(*g*) Steam passes from the steam box to the exhaust pipe.

What are the essential differences between: (*a*) steam and gasoline engines; (*b*) gasoline engines and Diesel engines; (*c*) automobile and airplane engines; (*d*) a refrigerator and a steam engine?

How many calories of heat are required (theoretically) to raise a mass of one ton four hundred feet? In actual practice, if the operation is done by a crane operating through a steam engine, we find we must use sufficient coal to produce ten times the amount of heat calculated according to theory.

The operation of the automobile engine is usually resolved into a cycle of four strokes. Describe briefly the function of each stroke.

Discuss briefly the first and second laws of thermodynamics and show why a perpetual motion machine is impossible.

If the hand is placed against the back of a household refrigerator while it is in operation, heat is felt. Explain.

Discuss the effect of the development of steam engines on the social structure of Europe from 1850 to 1900 and on that of America during the same interval.

Mark true or false:

A heat engine:

.... transforms heat into work.
.... transforms work into heat.
.... would have an efficiency of 100 per cent if it were not for frictional losses.
.... can operate continuously in surroundings which are at constant temperature.
.... can operate only when heat can be supplied to it at a high temperature and be removed at a low temperature.

.... has a theoretical efficiency equal to the temperature difference divid by the higher temperature.

.... would have a theoretical efficiency of 100 per cent if the exhaust w at the absolute zero.

12. Circle the letter or letters of the words or phrases which make the stateme correct:

a b c d e Heat engines include (*a*) generators; (*b*) steam engines; (*c*) gasol engines; (*d*) Diesel engines; (*e*) transformers.

a b c d e Most automobile engines are (*a*) steam; (*b*) Diesel; (*c*) gasoli (*d*) hot air; (*e*) four-cycle internal combustion.

a b c d e The Diesel engine differs from the gasoline engine in that (*a*) it has carburetor; (*b*) it runs at very high compression; (*c*) it uses chea fuel; (*d*) no spark is necessary; (*e*) it is more efficient.

a b c d e In the cylinder of a 4-cycle gasoline engine the following steps t place (*a*) compression; (*b*) sucking in of explosive mixture; (*c*) driv out of exhaust gases, (*d*) mixing of gasoline and air; (*e*) explosion. The order of these steps is .....

FOR FURTHER READING

1. Mott-Smith, M., *Heat and Its Workings.*
Chapters 3, 5, and 6 consider the behavior of a perfect gas, change of state, the topic of latent heat.

2. Croft, Terrell W., *Practical Heat.* Revised by R. B. Purdy; 2d editi New York: McGraw-Hill Book Company, 1939.
A book for the practical engineer. Chapters 1, 2, and 5 deal with matter, h temperature, and transfer of heat. Chapters 11 and 12 deal with steam vapor cycles. Chapters 15 and 16 discuss the modern steam power plants internal combustion engine power plants.

3. Taylor, L. W., *Physics.*
Chapter 22 discusses the principles of thermodynamics. Chapter 23 give rigorous discussion of heat engines.

4. Degler, Howard E., *Internal Combustion Engines.* New York: John Wi and Sons, 1938.
This book is primarily designed for the student interested in engineering. gives the theory, design, and application of internal combustion engines.

5. Mumford, Lewis, *Technics and Civilization.* New York: Harcourt, Br and Company, 1934.
This book is written primarily for the general reader. It attempts to tr the chief motives for the development of machines and the radical transfor tions of the social environment and the routine of life brought about by their Chapters 1 and 2 are recommended for a survey of the early development machines.

CROWTHER, J. G., *Social Relations of Science.* New York: The Macmillan Company, 1941.

This is a very good book. It attempts to analyze the connection between the work of the scientists and the social and economic developments occurring around them.

22

Combustion; Chemical Changes

IN THE PRECEDING CHAPTERS the nature of heat and its transformation mechanical energy in the steam engine and internal combustion eng were discussed. In all heat engines suitable fuels — coal, petroleum, gas — are consumed. The chemical transformation which fuels undergo order to produce heat is called *combustion*. Although fuels had been u lized for thousands of years for warmth, cooking, and metallurgical ope tions, the nature of combustion or burning was not known until about time of the American Revolution, and after the invention of the ste engine.

In this chapter combustion will be considered in some detail as an int duction to the many transformations of matter commonly called chemi changes. The quantitative principles which govern such changes, the c cept of the atom and of the molecule, and the symbolism used by the che ist will be included.

Matter

It may be recalled that matter and its classification were discus briefly as an introduction to the study of rocks and minerals (Chapter The numerous and varied materials found in nature are nearly all *mixtu* of different substances. They are usually heterogeneous (not unifo throughout); they vary in composition, that is, in the percentages of different components; and their characteristics or properties may be p dicted from those of the component substances. Mixtures may be se rated by physical, mechanical, or chemical methods. For example, i mixture of sugar and sand, however finely divided, the particles of the substances may be recognized if magnified. The proportion or percent of sand or sugar may be altered at will. If more sugar is added, the mixt becomes sweeter; if more sand is added, it becomes more gritty; in eit case the properties of both components can still be recognized. The cent of either component may vary from almost zero per cent to alm one hundred per cent. The density of the mixture is somewhere betw

ose of the two substances, and the one substance, sugar, dissolves in ter while the sand does not. The latter difference in solubility may be ed to separate this particular mixture into its components.

If all the natural mixtures found on this planet were separated into their mponents, tens of thousands of *substances* would be obtained. Each of ese substances is homogeneous (uniform throughout), is of a definite and aracteristic composition, and has specific properties; that is, for a given bstance the properties are always the same regardless of the source and st history of the substance. Samples of pure water obtained by distilla- n of sea water, well water, or rain, or prepared by the chemical combina- n of hydrogen and oxygen are identical in every respect. Samples of re oxygen, whether obtained from the air (a mixture) or from a com- und, have identical properties.

Nearly all of the many substances may by chemical means be separated o simpler or less complex substances, and are thus called *compounds*. ater may be decomposed to yield oxygen and hydrogen; or, it may be pared by a chemical union (burning) of oxygen and hydrogen. Both ocesses are experimental evidence that water is a compound. Other sub- nces cannot by chemical means be separated into simpler substances; se are called *elements*. The number of known elements is ninety-six. veral of them are not found in nature, but have been prepared by ificial means (see Chapter 27). Oxygen, hydrogen, copper, and gold, example, are elements.

The above definitions of compound and element are based on sound perimental evidence. To interpret experimental facts and to make pos- le the prediction of new reactions and chemical phenomena, two the- tical concepts are necessary. The first is that of the *molecule*, evidence the existence of which was given in Chapter 20. The smallest particle a substance (element or compound) which retains the characteristics d composition of the bulk substance is known as a *molecule*. If a crystal sugar is divided and subdivided into smaller and smaller particles, a nt will be reached, at least in the imagination, where the particles are so all that with further division they would no longer be sugar. These all particles are molecules.

The second theoretical concept is that of the atom. Were the sugar rticles (molecules) divided further, smaller particles of other substances, sugar, would result. The division could be extended, again in the agination, until several varieties of particles are obtained, none of which n be further subdivided by chemical means. These are the smallest units the elements carbon, hydrogen, and oxygen, of which the sugar mole- es are composed, and are called *atoms*. By definition the atom is the allest particle of an element which enters into a chemical change. Mole- es of elements and of compounds are composed of atoms. For some ments such as helium, the molecule and atom may be regarded as identi-

cal, that is, the molecule consists of only one atom. Molecules of some the other elements contain more than one atom; the molecules of ordina oxygen and certain forms of sulfur contain two and eight atoms respe tively. A molecule of a compound must contain at least two dissimil atoms, and unusually large molecules may contain up to several thousa atoms. No one has ever seen an atom, but the evidence for the existen of atoms is such that the concept and theory are universally accepte The experimental basis of the atomic theory, its development, and i application to the interpretation of chemical changes will be presente after a consideration of combustion.

Combustion as a Chemical Change

Burning or combustion is a familiar and extremely important phenom non. The burning of wood, coal, gasoline, gas, and other fuels and co bustible materials produces visible light, usually a flame, sometimes smok and always heat. However, fire, which is now so easy to kindle, and whi was formerly regarded as the property of the gods and the home of t spirits, is the result of *chemical change.* That these changes involve t transformation of one kind of matter into another may be demonstrate The burning match gives off smoke and a number of gaseous materials, a leaves a fragile piece of charcoal; burning hydrogen leaves no solid residu but if the vapor it gives off is condensed, it is found to be water; gasoli burns, forming water and carbon dioxide. In all cases the substanc formed are different in properties and composition from the initial su stances. It may also be demonstrated that something in the air is requir in ordinary combustion; a burning match or candle covered by an invert jar containing air soon stops burning. It is commonly known that the su stance in the air essential to combustion is oxygen. A piece of burning wo burns brighter and faster when thrust into a bottle containing only oxyg but is extinguished when placed in a bottle containing only nitrogen, t other principal component of the air.

In the above examples, many of the products of combustion are gas and unless the reactions are carried out in closed vessels they escape i the air, a fact which led to the formulation of one of the earlier incorr theories of combustion. The procedure may be simplified by using a so substance which burns to yield a solid product. Magnesium, a brig silver-white metal with characteristic hardness, density, and other prop ties, is ignited by being held in a flame. It bursts into a brilliant flame a burns (Figure 251), yielding a white powder substance (Figure 252) w entirely different properties from those of the metal. If the white su stance is gathered up and weighed, it is found to have a *greater* mass th the original piece of magnesium.

Combustion may therefore be summarized as a chemical change which a substance generally combines with oxygen at a rapid rate with

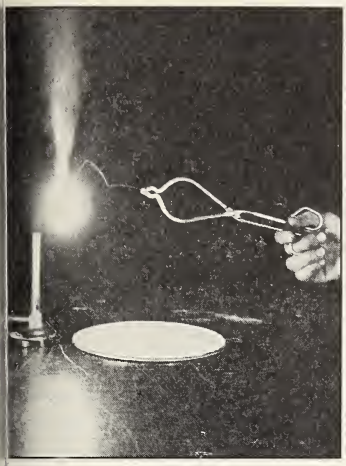


FIGURE 251

f a strip of magnesium ribbon is held by ns of iron tongs near a flame, it soon sts into a brilliant flame and burns . . .

FIGURE 252

. . . leaving a white powdery ash.

olution of visible light and energy in the form of heat. However, com- stion may take place more slowly and at lower temperatures. The rust- of metals is a slow oxidation in which the metal combines with oxygen produce, in most cases, the same oxide (rust) as in the more rapid proc- , and the same quantity of heat. The high temperatures are not at- ned, because of the longer period of time required. In the human body d in the bodies of other animals food is oxidized, slowly generating heat maintain body temperature.

There are also rapid chemical changes which produce heat and flames, t in which oxygen is not involved. Hydrogen "burns" in chlorine with ale flame to form hydrogen chloride; tin also burns in chlorine, forming chloride.

Combustion, however, is only one type of chemical change; there are ny others. In all cases, nevertheless, new substances are formed and rgy in some form is involved, and is either generated or absorbed by the ction. The quantitative aspects of chemical change, that is, the princi- that substances always combine with each other in definite proportions der specific conditions, and the principle that no appreciable quantity of tter is created nor destroyed during a chemical change will be discussed er some of the earlier concepts and theories have been considered.

A substance may also undergo *physical change*, that is, a change of state lid, liquid, or gaseous) or form, without alteration of all of the proper- s and with no change whatsoever in its chemical composition. The

evaporation of water, the melting of a solid, or the freezing of a liquid, t change of a solid substance from one crystalline form to another, are e amples of physical change.

Early Ideas about Chemical Change

The historical development of the present ideas of chemical reactio and their interpretation on the basis of the atomic theory may be rough divided into three periods: (1) that of the ancients, that is, the Egyptia Greek, and Eastern philosophers and artisans; (2) the period of the alche ists; and (3) the modern period.

The Ancients. The science of chemistry may be said to have originat in Egypt when in the famous university at Alexandria the practical know edge of the artisans who worked with metals, glass, pottery, paint and dyes was blended with the speculations of the Greeks and Easte philosophers. The philosophers, recognizing the unity and uniformity nature, attempted to find the primordial elements from which the kno universe was made. The first primordial element was water, in whi there are so many living things and dissolved substances, and which essential to life. Air, fire, and earth were added, and were regarded Empedocles as unalterable. The theory of the four elements taught Aristotle assumed a fundamental *matter-stuff* upon which qualities li coldness and dryness could be impressed to give one of the primal elemen For example, the combination of wetness and heat with the matter-st gives air, dryness with cold gives earth, dryness with heat gives fire, w ness with cold gives water. This doctrine gave stimulus and direction chemistry primarily because it held that one kind of matter could changed to another kind, that is, transmutation of the primal elements w possible. Water could be changed to earth if its wetness were overcome dryness; it could be changed to air if its coldness were overcome by he

The ancient philosophers also made some ingenious speculations on t ultimate composition of matter. Empedocles (*circa* 450 B.C.), Democrit (*circa* 400 B.C.), and others assumed that the so-called elements and t known substances consisted of very small, indivisible and indestructi particles which they called *atoms* (indivisible). The atomism of the a cients was a philosophic and speculative theory rather than a scienti doctrine, and was not based on experimental facts, nor was it used by th who actually worked with matter. It is also evident that the philosophe due to lack of quantitative data, failed to distinguish between atoms a molecules. While their theory preceded the more recent atomic theory more than two thousand years and probably had some suggestive influe in its formulation, there is little correlation between the two.

The Alchemists. The people along the valleys of the Nile, the Euphrat and the Indus had worked on metals before Herodotus published t world's first history; Pharaoh Senfru had worked the copper mines

ıai, and gold was extracted by the priests with a full ritual of magic and ·recy. In Egypt, the artisans developed practical metallurgy and ex-·imentally learned to improve the color of metals. Having absorbed, at st superficially, some of the Greek philosophy, they slowly came to nk that all metals have a common element, and that specific metals ed their individual characteristics to differences in color and fusibility. These artisans became the alchemists, and adopted the idea prevalent er the time of Plato and Aristotle that everything tended to change vard perfection, gold being the most perfect of metals. It was therefore umed that a base metal like copper or lead would under treatment by eral secret processes and heatings change its color and become the oble" metal, gold.

By the third and fourth centuries A.D. the Alexandrian alchemists ab-bed the religious ecstasy of the times, and filled their writings with un-entific mysticism. In this form alchemy passed into the hands of the abs, who conquered Egypt in the seventh century, and who brought h them a new spirit of inquiry. When the Arabs extended their empire Spain they took with them their knowledge of Greek science and medi-e, including alchemy. Beginning with the eleventh century this knowl-ge spread over Europe, mostly by way of Latin translations. During the ddle Ages alchemy came to mean the search for the "philosopher's ne," which would change base metals into gold, and which would also ve as an "elixir of life," thus giving expression to two desires of man-ıd. The writings of the alchemists during this period were couched in)tle terms, meaningless to the uninitiated, and perhaps understandable y to the practitioners of the art.

The alchemists thus fell into disrepute, and the inquiries and investiga-ns concerning metals and other substances were gradually taken over by)se who were more scientific and thus free from the magic tenets of al-·my. However, the chemists owe considerable knowledge to the alchem-s. Despite the fraudulent practices of some, the alchemists gathered ts, combined some of the philosophy of the Greeks with practical ex-·imentation, made many great discoveries both in chemistry and medi-e, and formulated the problem of transmutation not so long ago solved modern physical science. When it is recalled that so great a scientist as wton accepted alchemy, it is apparent that the problem of judgment of work and achievement is a complex one. We may therefore consider hemy, pseudoalchemy, and chemistry as stages in man's developing ıcept of matter.

e Nature of Combustion

The Greeks believed that all combustible substances contained an ele-nt *fire*, which they called *theion*, a word which may be translated either "godly," "spirit," or "sulfur." The alchemist identified the element of

fire with the sulfur of the Greeks, and assumed that all combustible su stances gave off this element when burning. About 1700 Becher a Stahl, in attempting to interpret the burning of metals, adopted this e planation of combustion, but called the principle of fire *phlogiston* (*phlo phlogos* = flame). Charcoal, metals, coal, and all other combustible su stances, according to this theory, contained phlogiston which they lo upon burning, the resulting ash or product of combustion containing phlogiston. A metal or charcoal burned to give the calx or oxide:

$$\text{Metal (on burning)} \longrightarrow \text{calx} + \text{phlogiston}$$
$$\text{Charcoal (on burning)} \longrightarrow \text{ash} + \text{phlogiston}$$

To obtain the metal from the calx or oxide it was heated with a combustil material which gave it phlogiston to form the metal:

$$\text{Metallic calx} + \text{phlogiston} \longrightarrow \text{metal}$$

According to this theory, the burning candle when placed under a gl soon goes out because the air in the jar becomes saturated with phlogist and can accept no more; the air must then be dephlogisticated before it c support combustion again. This theory was accepted for a time because was compatible with the known facts. However, a number of factors finally result in its rejection, and for it there was substituted the oxidati interpretation of burning. In the first place, no one had ever in any w been able to observe or isolate this subtle substance, phlogiston. Secon the element oxygen was discovered and its presence in the air demo strated. But the third factor, which was crucial, and which was demo strated by use of the balance, was that metals *gain* in weight when burn That is, the calx which was supposed to be formed by *loss* of phlogiston h a greater mass than the original metal.

When Joseph Priestley (Figure 253) discovered oxygen in 1774 by he ing mercury oxide, he called it "dephlogisticated air," for he reasoned th things burned more quickly in this gas because it was more hungry phlogiston. Priestley thus missed the implication of his great discove A brilliant non-conformist English minister, he later sought refuge America from mob intolerance, and lived the remainder of his life in Nor umberland, Pennsylvania. He staunchly adhered to the phlogiston theo as is evident from his last publication, *Doctrine of Phlogiston Establishe*

In France, in the meantime, Antoine Lavoisier (Figure 254) had c ducted extensive experiments on the heating of metals in air, using for first time in chemical investigation a sensitive balance or scale, and prov that metals gain in weight to form the oxide. Lavoisier was visited Priestley soon after the latter discovered "dephlogisticated air," and s thereafter this substance was named *oxygen* by Lavoisier. He also repea the work of Priestley, and extended it quantitatively, showing that a m heated in an enclosed vessel gained in weight by an amount correspond

proximately to the decrease in eight of the air in the vessel. Upon ating the oxide more strongly, he tained the metal and a volume of ygen substantially equal to that iginally consumed by the burning etal. Here, then, was the qualita- ve and quantitative proof of the na- re of burning or combustion; com- nation of the combustible material th a definite quantity of oxygen thout any change in the total mass matter involved.

Lavoisier, often regarded as the under of modern chemistry, held a mber of offices in the French gov- nment; he was Director of Muni- ns and Director of the Academy of ience. A wealthy and outstanding votee of the idea of constitutional narchy, he was a member of the ted *Ferme*, a private company em- wered to collect taxes on tobacco d salt, a privilege for which it paid e state an agreed sum. This posi- n brought him considerable income, but was also the basis of accusations ade against him during the Revolution. He was brought to trial on arges which to us today may seem insignificant and false. But revo- ions result from long-accumulated injustices and oppressions, and do t respect individuals. Lavoisier, with twenty-eight others, was guil- ined on May 8, 1794. His work, however, *Traité Elémentaire de Chimie*, nds with Galileo's *Dialogues* and Newton's *Principia*, and became the ndation on which the chemistry of the nineteenth century was con- ucted.

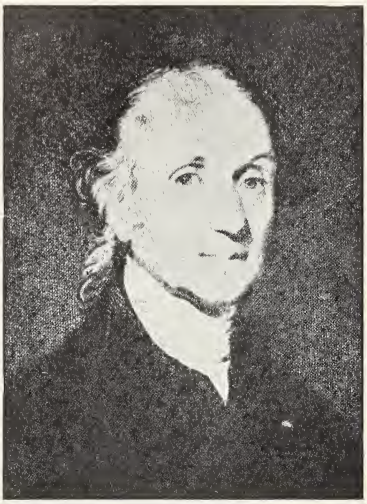


FIGURE 253. JOSEPH PRIESTLEY

English clergyman chemist who emigrated to America because of religious and political intolerance. Discoverer of oxygen and defender of the phlogiston theory. (*Courtesy of Journal of Chemical Education*)

Quantitative Study of Chemical Change

It was pointed out earlier in this chapter that two given elements com- ne with each other in a definite proportion by weight under specific condi- ns, but no experimental proof was given. Hence the experiment in ich magnesium is burned to form the oxide may be repeated here, but on quantitative basis. Since magnesium may combine with nitrogen as well with oxygen when burned in air, an apparatus shown diagrammatically in gure 255 is arranged so that only pure oxygen flows through the tube in ich the magnesium is placed. First the empty crucible is weighed, and

then the magnesium is placed in it and both are weighed, the difference weight being the weight of the metal. The crucible is lightly covered ar placed in the combustion tube. Oxygen flows from the cylinder, any moi ture in it is removed by a drying substance in the U tubes, and after the a in the system has been displaced by the dry oxygen, the tube is heate After about fifteen minutes the heating is discontinued, the crucible allowed to cool, and is weighed again. From the data obtained the amou of oxygen which combines with one gram of magnesium is calculated:

Weight of crucible and magnesium	18.943 g
Weight of empty crucible	18.468 g
Weight of magnesium	0.475 g
Weight of crucible and contents after heating	19.252 g
Weight of crucible and magnesium before heating	18.943 g
Gain in weight due to combustion with oxygen	0.309 g

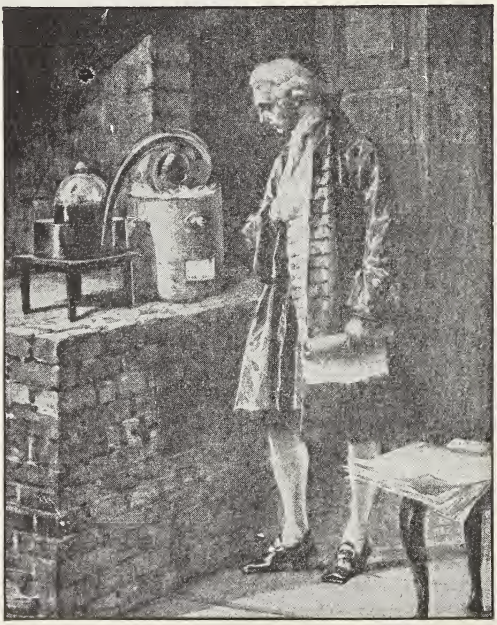


FIGURE 254. ANTOINE LAURENT LAVOISIER

One of the founders of modern chemistry. A pioneer in the use of the quantitative bala for the study of chemical changes. He was a victim of the French Revolution, being execu in May, 1794.

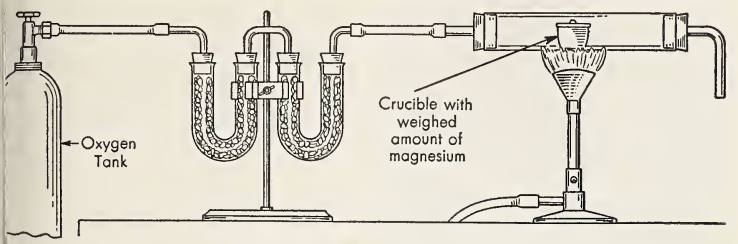


FIGURE 255. APPARATUS FOR DETERMINING THE WEIGHT OF OXYGEN WHICH COMBINES WITH A DEFINITE AMOUNT OF MAGNESIUM

Since 0.475 g of magnesium combines with 0.309 g of oxygen, therefore 00 g of magnesium combines with 1.000 g/0.475 g × 0.309 g = 0.651 g oxygen. The experiment is repeated several times with results which y vary slightly due to experimental error, but which show that a given ight of magnesium always combines with the same amount of oxygen to m magnesium oxide. For example, the amounts may be 1.000 : 0.651, 00 : 0.658, and 1.000 : 0.660; the average of the results is 1.000 : 0.656. If the experiment is reversed, that is, if one starts with a known amount magnesium oxide and by appropriate chemical reactions separates the gnesium from the oxygen, the relationship is found to be the same; from 56 g of the oxide, 1.000 g of the metal is obtained. It must therefore low that the weight of the magnesium oxide is equal to the combined ights of the magnesium and the oxygen, and that the composition of the npound is constant regardless of its source and the method of determina- n.

$$\underset{1.000\text{ g}}{\text{Magnesium}} + \underset{0.656\text{ g}}{\text{oxygen}} \longrightarrow \underset{1.656\text{ g}}{\text{magnesium oxide}}$$

d to obtain the percentage or "parts per hundred":

$$\frac{1.000}{1.656} \times 100 = 60.39\% \text{ magnesium}$$

$$\frac{0.656}{1.656} \times 100 = 39.61\% \text{ oxygen}$$

Other compounds may also be examined; for example, water, whose nposition may be determined either by combining hydrogen with oxygen nthesis) to form water, or by the decomposition (analysis) of the com- und into the two elements. All methods show for *pure* water, regardless its source, a composition of 11.19 per cent hydrogen and 88.81 per cent ygen. This uniformity in the behavior of elements which results in the mation of compounds of constant composition is known as the *Law of*

constant composition, or of *Definite proportions*. It may be formally state*In every pure compound the relative proportions by weight of the eleme present are constant and independent of the source or previous history of t compound*. For example, when element A combines with element B form the compound AB, and the weights of the elements and the compou are represented by these letters, then

$$A + B \longrightarrow AB, \quad \frac{A \times 100}{AB} = \text{per cent A}, \quad \frac{B \times 100}{AB} = \text{per cent B}$$

From the above experiments, another principle becomes apparent, namel that of *conservation of mass*. In all chemical changes, there is no weighab loss or gain in mass, and the sum of the masses of the reacting substances the same as the sum of the masses of the products.

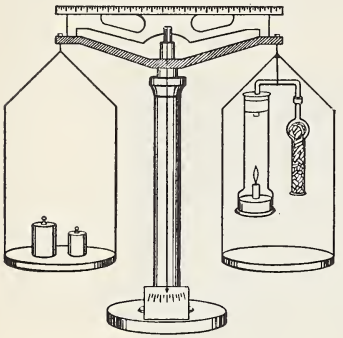


FIGURE 256. APPARATUS TO SHOW THAT AS A CANDLE BURNS IT BECOMES HEAVIER

In all reactions such as the burni of wood, coal, or candles, there is a apparent loss of mass, for some the products of combustion are gas These may be collected and weighe however, to show that there is deviation from the principle. In t experiment (Figure 256) a candle placed in one pan of a balance a over it a glass chimney which contai material to absorb the products combustion. On the other pan enou weights are placed to counterbalan the load exactly, and the candle then lighted. As the candle burn the pan in which it is suspended slow descends, showing a gain in weigh The gain in weight may be expe mentally shown to be equal to the amount of oxygen consumed by t burning candle.

The Atomic Theory

After Lavoisier had demonstrated the usefulness of the analytical b ance in experimental chemistry, considerable quantitative information chemical reactions was obtained. From these data a number of fund mental laws or principles were formulated inductively, and among the the two principles stated in the previous section, the law of definite propo tions and that of conservation of mass. The interpretation of these a other related principles was undertaken by John Dalton, an English scho master, who proposed in 1803 a scientific atomic theory.

Dalton assumed, as did the Greek philosophers, that all substances a

mposed of tiny indivisible and in-structible particles which he, also, lled atoms. His hypothesis differed)m the atomism of the Greeks in at it assigned specific physical aracteristics to the atoms and was erefore used to account for and correlate the known experimental :ts concerning chemical reactions. Dalton's original hypothesis was sed upon insufficient facts, it is later necessary to modify certain)ects of it when new facts were dis-vered. Nevertheless, the essential ncept has survived a century and half of chemical development, and e atomic theory today is the estab-hed and accepted basis of thought d experiment in chemistry and ne of the other physical sciences. The assumptions of the modern-d atomic theory are as follows: (1) l chemical elements are composed of)ms, and the atoms of a particular ment are all alike in chemical characteristics and average mass. (2) oms of different elements have different properties and average masses.) Atoms of different elements unite chemically to form molecules of com-unds and under given conditions the number of atoms of the different ments which unite with each other to form a molecule is fixed and spe-ic, depending upon the characteristics of the particular elements in-lved. For example, the hydrogen chloride molecule contains one atom hydrogen and one atom of chlorine; a molecule of water contains two)ms of hydrogen and one atom of oxygen; a molecule of aluminum oxide ntains two atoms of aluminum and three atoms of oxygen. All mole-les of a given compound are exactly alike in properties and composition, d molecules of different substances differ from each other in properties d composition. (4) Two or more atoms of the same kind may unite to m a molecule of the element. (5) Although the atom is now known to a complex structure (Chapter 26) and *not* indivisible and indestructible, ese characteristics do not in any way impair the usefulness nor the valid-of the atomic theory.

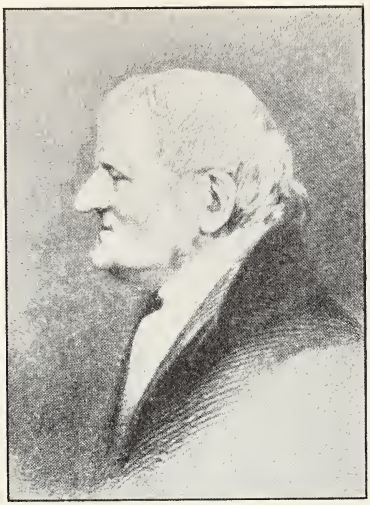


FIGURE 257. JOHN DALTON

English schoolteacher and scientist. Although atomic concepts occur in various early speculative philosophies, Dalton is generally regarded as the enunciator of the first truly scientific atomic theory.

The above assumptions account quite satisfactorily for the facts and inciples which have been discussed in connection with chemical changes. a molecule of a compound consists of a definite number of atoms of each

constituent element and if the atoms of each element have a specific ave age mass, then the law of definite proportions must follow. The compoun must therefore always contain a definite and constant percentage of ea element by weight. For example, if two atoms of a certain element uni with three atoms of a second element to form a molecule of a compoun and if the masses of the atoms of the two elements are A and B respe tively, then the mass of a molecule is 2 A + 3 B. The masses of the tw elements in a molecule of the compound are 2 A and 3 B, and the compos tion of a molecule of the compound is:

$$\frac{2\,A \times 100}{2\,A + 3\,B} = \text{percentage of A}$$

and

$$\frac{3\,B \times 100}{2\,A + 3\,B} = \text{percentage of B.}$$

Since all molecules of a given substance are alike in composition and pro erties, the above composition holds for any amount or any sample of th compound.

During a chemical change the original molecules are destroyed and fro their fragments new ones are formed with the same total number of aton of each element initially present. Since the atoms are not destroyed bu simply redistributed or interchanged, there is no loss or gain in the tot mass of matter involved.

The atomic and molecular theories also permit matter to be classifie and the different classes to be differentiated and redefined. A mixture co tains *more than one* kind of molecule, while a substance (element or com pound) consists of *only one* molecular species. An element is a substan whose molecules contain *only one* kind of atom, while a compound is a su stance whose molecules contain *more than one* atomic species. These tern were previously defined on the basis of experiment.

Atomic and Molecular Weights

An atom is a particle of extremely small size and mass. A copper ato for example, has a radius of 1.3×10^{-8} centimeters, and a mass of appro imately 10^{-22} grams. These values are different for each element, but b relatively small factors. To isolate and handle a single atom for dire weighing is not possible, for it cannot be seen by the most powerf optical microscope. Even if this were possible, no device sensitive enou to directly measure its weight has been developed; the smallest mass whi can at present be weighed with any degree of accuracy is 10^{-6} to 10 grams. It is therefore necessary to experiment with larger and weighab quantities of elements and compounds and to determine the weights each of the atoms by indirect methods. (For more direct physic methods, see Chapter 25.)

The actual weights of the atoms of the respective elements, however etermined, are very small numbers, as shown above for the copper tom. It is simpler and better to use a system of *relative* weights, with umbers of more convenient size, based upon some arbitrarily selected tandard. For example, the actual weight of an oxygen atom is 2.7×10^{-23} rams, and that of a sulfur atom is 5.3×10^{-23} grams. Since the latter is pproximately twice the former, the relative weights of the two atoms may e expressed as 1 and 2, or 5 and 10, or 35 and 70, etc. Obviously, some tandard must be adopted, and the one selected by international agreement nd adhered to by all chemists is the average weight of naturally-occurring xygen atoms taken as 16.0000. With this standard, the relative weight of ne sulfur atom is about 32, and that of the hydrogen atom, the lightest of l atoms, is about 1. *The relative weights of the various atoms based upon the rbitrarily fixed standard of oxygen, 16.0000, are known as the atomic weights.* hey are expressed as pure numbers, and the *atomic weight unit*[1] is one-xteenth of the atomic weight of oxygen. On this scale the atomic weight uranium, which is the largest of those of the naturally-occurring ele-ents, is 238.07/16 times that of the oxygen atom, or 238.07 atomic weight nits. Table 32 is a list of atomic weights of the elements arranged in ap-roximately increasing order, or by the ordinal or atomic number, the sig-ficance of which will be discussed in Chapter 25. A table of the elements ranged in alphabetical order is inside the front cover.

Atomic weights may be determined by a number of different chemical ethods; the most accurate and commonly employed procedure is to easure the quantity of one element combining with another. If the omic weight of one of the elements entering into the chemical combina-on is known, or arbitrarily fixed, and the number of atoms of each ele-ent in a molecule of the compound is known, the atomic weight may be lculated. In Table 33 the analyses of a number of oxides, obtained ther by combination of the elements, as in the case of magnesium and ygen to form magnesium oxide, or by decomposition of the compound, as the electrolysis of water to give hydrogen and oxygen, are shown. For nvenience the quantity of oxygen involved is taken as 16.0000 grams, or me multiple of 16.0000 grams, rather than the smaller quantities used in e experimental procedures.

It may be noted from Table 33 that 2.0160 grams of hydrogen com-ne with 16.0000 grams of oxygen to form water. If the molecule of water ntains, as Dalton assumed, one atom of hydrogen and one atom of oxygen, en the relative weights of the atoms are respectively 2.0160 and 16.0000; on the other hand, the water molecule contains (as it actually does) *two* oms of hydrogen and one of oxygen, the atomic weights are 1.0080 and .0000. The methods whereby the relative number of atoms in a molecule

[1] It has been suggested that the atomic weight unit be called the *avogram*.

Table 32. The Chemical Elements

Atomic Number	Element	Symbol	Atomic Weight	Atomic Number	Element	Symbol	Atomic Weight
1	*Hydrogen*	H	1.0080	43	Technetium	Tc	?
2	*Helium*	He	4.003	44	Ruthenium	Ru	101.7
3	Lithium	Li	6.940	45	Rhodium	Rh	102.91
4	Beryllium	Be	9.02	46	Palladium	Pd	106.7
5	Boron	B	10.82	47	*Silver*	Ag	107.880
6	*Carbon*	C	12.010	48	Cadmium	Cd	112.41
7	*Nitrogen*	N	14.008	49	Indium	In	114.76
8	*Oxygen*	O	16.0000	50	Tin	Sn	118.70
9	*Fluorine*	F	19.00	51	Antimony	Sb	121.76
10	*Neon*	Ne	20.183	52	Tellurium	Te	127.61
11	*Sodium*	Na	22.997	53	*Iodine*	I	126.92
12	*Magnesium*	Mg	24.32	54	*Xenon*	Xe	131.3
13	*Aluminum*	Al	26.97	55	Cesium	Cs	132.91
14	*Silicon*	Si	28.06	56	Barium	Ba	137.36
15	Phosphorus	P	30.98	57–71	The Rare Earths	—	—
16	*Sulfur*	S	32.066				
17	*Chlorine*	Cl	35.457	72	Hafnium	Hf	178.6
18	Argon	A	39.944	73	Tantalum	Ta	180.88
19	*Potassium*	K	39.096	74	Tungsten (Wolfram)	W	183.92
20	*Calcium*	Ca	40.08				
21	Scandium	Sc	45.10	75	Rhenium	Re	186.31
22	Titanium	Ti	47.90	76	Osmium	Os	190.2
23	Vanadium	V	50.95	77	Iridium	Ir	193.1
24	Chromium	Cr	52.01	78	Platinum	Pt	195.23
25	Manganese	Mn	54.93	79	Gold	Au	197.2
26	*Iron*	Fe	55.85	80	*Mercury*	Hg	200.61
27	Cobalt	Co	58.94	81	Thallium	Tl	204.39
28	Nickel	Ni	58.69	82	Lead	Pb	207.21
29	*Copper*	Cu	63.54	83	Bismuth	Bi	209.00
30	*Zinc*	Zn	65.38	84	Polonium	Po	210±
31	Gallium	Ga	69.72	85	Astatine	At	?
32	Germanium	Ge	72.60	86	*Radon*	Rn	222
33	Arsenic	As	74.91	87	Francium	Fr	?
34	Selenium	Se	78.96	88	*Radium*	Ra	226.05
35	*Bromine*	Br	79.916	89	Actinium	Ac	227
36	*Krypton*	Kr	83.7	90	Thorium	Th	232.12
37	Rubidium	Rb	85.48	91	Protoactinium	Pa	231
38	Strontium	Sr	87.63	92	*Uranium*	U	238.07
39	Yttrium	Y	88.92	93*	Neptunium	Np	239±
40	Zirconium	Zr	91.22	94*	Plutonium	Pu	239±
41	Niobium	Nb	92.91	95*	Americium	Am	242±
42	Molybdenum	Mo	95.95	96*	Curium	Cm	243±

* Elements 93–96 are synthetic elements, and the atomic weights have only been inferre

TABLE 33. AMOUNTS OF VARIOUS ELEMENTS COMBINING WITH SPECIFIED QUANTITIES OF OXYGEN

Oxygen	16.0000	grams	+ hydrogen	2.0160	grams	= 18.0160	grams	water
"	32.0000	"	+ hydrogen	2.0160	"	= 34.0160	"	hydrogen peroxide
"	16.0000	"	+ nitrogen	14.008	"	= 30.008	"	nitric oxide
"	16.0000	"	+ nitrogen	28.016	"	= 44.016	"	nitrous oxide
"	16.0000	"	+ carbon	12.01	"	= 28.01	"	carbon monoxide
"	32.0000	"	+ carbon	12.01	"	= 44.01	"	carbon dioxide
"	16.0000	"	+ magnesium	24.32	"	= 40.32	"	magnesium oxide
"	16.0000	"	+ calcium	40.08	"	= 56.08	"	calcium oxide
"	16.0000	"	+ iron	55.85	"	= 71.85	"	iron oxide
"	16.0000	"	+ copper	63.57	"	= 79.57	"	copper oxide

f a compound is determined need not be discussed in detail at this point. he number of atoms of each element in a molecule may be derived if the olecular weight of the compound is known, and if a sufficiently large umber of compounds of a particular element is studied.

It was shown previously that larger quantities of materials than single toms must be used, but the atomic weights serve as a basis. The atomic eights of oxygen and nitrogen are 16.0000 and 14.008 respectively. It llows that quantities of these two elements which are in proportion to the tomic weights contain the same number of atoms, for example, 8.0000 rams of oxygen and 7.004 grams of nitrogen, or 1 gram of oxygen and 4.008/16.0000 grams of nitrogen. A convenient amount to consider is a umber of grams numerically equal to the atomic weight, i.e., 16.0000 rams of oxygen, 14.008 grams of nitrogen, etc. These quantities are lled *gram atomic weights*, and contain 6.023×10^{23} atoms. A gram is herefore 6.023×10^{23} times as heavy as an atomic weight unit. In gen- al, if the number a represents the atomic weight of an element, a grams is e gram atomic weight; the atomic weight of chlorine is 35.457, and the am atomic weight, containing 6.023×10^{23} atoms, is 35.457 grams.

From these data it may be seen how the actual weight of a single atom ch as copper, oxygen, or sulfur, shown previously, is calculated. The am atomic weight divided by 6.023×10^{23} gives the weight of one atom; r oxygen: $16.0000 \text{ g}/6.023 \times 10^{23} = 2.7 \times 10^{-23}$ g.

The *molecular weight* of a substance (element or compound) is the relative eight of a molecule as compared to the oxygen atom, which is 16.0000 or the oxygen molecule (O_2) which is 32.0000. The same standard is em- oyed for molecular weights as for atomic weights. The molecular weight water is 18.0160, that is, 18.0160 atomic weight units, which means that e weight of the water molecule is 18.0160/16.0000 times that of the oxy- n atom or 18.0160/32.0000 times that of the oxygen molecule. The *am molecular weight* bears the same relationship to molecular weight as a am atomic weight bears to atomic weight. If m represents the molecular eight of a substance, m grams is the gram molecular weight or *mole*. Simi- rly, a gram molecular weight contains 6.023×10^{23} molecules. For ex-

ample, a gram molecular weight or mole of water is 18.0160 grams, and it contains 6.023×10^{23} molecules. From these figures, the weight of a single molecule may be calculated. The experimental methods for determining molecular weights are not discussed in this text. However, as shown in the next section, the molecular weight may be calculated if the formula is known.

The number 6.023×10^{23} is known for historical reasons as Avogadro's number, and is represented by the letter N. One method used for the determination of this important quantity is given in Chapter 23.

Symbols and Formulas

In the preliminary discussion of elements and compounds and in the table of elements (Table 32), symbols were employed for the elements. A *symbol*, usually the first letter of the name of the element or the first letter and an additional letter, is not merely an abbreviation, but also has quantitative significance. For example, the symbols *C* for carbon, *Cl* for chlorine, *Co* for cobalt, *Cu* for copper, etc., imply one atom or one atomic weight, or one gram atomic weight of the respective element. The symbol *C*, then, represents 1 atom, or 12.010 atomic weight units of carbon; or, if gram weights are employed, 12.010 grams, which contain 6.023×10^{23} atoms. It is suggested that the symbols of the more common elements shown in italics in the table, be memorized.

A *chemical formula* represents a molecule of a substance, and the number and kinds of atoms of which the molecule is composed. The formula for ordinary oxygen is O_2, which means that the oxygen molecule consists of two atoms. Similarly, the molecules of a number of other common gaseous elements such as hydrogen, nitrogen, and chlorine, consist of two atoms and their formulas are H_2, N_2, and Cl_2, respectively. A carbon dioxide molecule consists of one atom of carbon and two atoms of oxygen; its formula is CO_2. A water molecule contains two atoms of hydrogen and one atom of oxygen, and is represented by the formula H_2O, the subscript denoting the number of atoms of the particular element for which it is written.

Chemical formulas are derived experimentally. For example, it is noted in Table 33 that 16.0000 grams of oxygen combine with 14.008 grams of nitrogen to form nitric oxide. Since these quantities represent one gram atomic weight of the respective elements, the simplest formula for nitric oxide is NO. Under other conditions, 16.0000 grams of oxygen or one gram atom enters into chemical combustion with 28.016 grams of nitrogen or two gram atoms to form nitrous oxide. The formula for nitrous oxide is therefore N_2O, that is, two atoms of nitrogen are combined with one of oxygen to form the nitrous oxide molecule.

It is possible then to determine the simplest formula of a compound from the experimentally determined composition, and the formula, once derived, indicates that composition. The simplest formula, while correctly

sed for many substances, is not in all cases the proper one. For example, n analysis of a compound shows that it contains approximately 7.7 per ent of hydrogen and 92.3 per cent of carbon, that is, 7.7 g of hydrogen to 2.3 g of carbon. Since these numbers are in approximately the same ratio s the atomic weights of the two elements, 1.0080 to 12.010, the simplest rmula is CH. However, no compound of carbon and hydrogen with a olecular weight of approximately 13, as indicated by the above formula, known. There are at least two compounds which contain 7.7 per cent ydrogen and 92.3 per cent carbon, and they might be any multiple of the rmula CH, that is, C_2H_2, C_3H_3, C_4H_4, etc. Before the correct one can be lected the molecular weight of the substance must be determined experi- entally. For one of the compounds it is 26. The *molecular formula* is herefore C_2H_2, and the substance is acetylene, a combustible gas. The her compound has a molecular weight of approximately 78, and its molec- ar formula is C_6H_6, benzene. These two compounds have quite different hysical and chemical properties, although they have identical chemical mpositions. It follows that the molecular formula which indicates not nly the composition but the molecular weight of the substance must be sed when known. In many cases, particularly for inorganic compounds, he simplest formula is also the molecular formula; HCl (hydrogen chlo- de), H_2O (water), and CCl_4 (carbon tetrachloride) are examples.

In other instances where the simplest formula is used, the molecular eight has not been determined, or it may be that molecules of the sub- ance under consideration do not exist. The formula used for silicon diox- e, which is sand (quartz), and certain other minerals, is SiO_2. A crystal quartz consists of an arrangement of silicon and oxygen atoms in which ch silicon atom is surrounded by four oxygen atoms and each oxygen om is between two silicon atoms — there are no molecules of SiO_2 — but r every silicon atom there are two oxygen atoms. The formula used is herefore SiO_2, which describes only the chemical composition.

A molecular formula does not show the arrangement of the atoms in a olecule. In Chapter 33 there is a detailed treatment of structural rmulas as used in organic chemistry.

After a formula is established, it may be used to calculate the molecular eight of the substance and its composition. The formula for carbon diox- e, for instance, is CO_2. The molecular weight is then the sum of the eights of all of the atoms in the molecule: $12.010 + 2 \times 16.0000 = 44.010$. he composition is:

$$\frac{12.010 \times 100}{44.010} = 27.29\% \text{ carbon}$$

nd

$$\frac{32.000 \times 100}{44.010} = 72.71\% \text{ oxygen}$$

Chemical symbolism may be summed up as follows: a *symbol* represent an *atom* of an element; a *formula* generally represents a *molecule* of a sub stance, which may be an element or a compound.

Chemical Equations

In a chemical equation, formulas are used to represent a chemical chang Before a chemical equation may be written, the correct formulas for th reacting substances and the products must be known. The burning c magnesium may be used to illustrate the steps in writing an equation. I has been shown that magnesium, whose formula is Mg (for most of th metals the molecule is assumed to consist of one atom), combines wit oxygen to form magnesium oxide. For beginners the equation is sometim written:

$$Mg + O \longrightarrow MgO$$

That is, one atom of magnesium combines chemically with one atom c oxygen to form a molecule of magnesium oxide. However, despite the fac that during the reaction single atoms of oxygen are involved, it is true tha ordinary oxygen is one of the initial substances and that its formula a previously shown has been experimentally established as O_2. It may als be established from the quantitative data described earlier in this chapte that the formula for magnesium oxide is MgO. The equation may ther fore be written:

$$Mg + O_2 \longrightarrow MgO$$

The arrow indicates the direction in which the reaction proceeds, and read as "reacts to give." The above equation is not "balanced," for w must, in conformity with the law of conservation of mass, account fo every atom, that is, there must be the same number of atoms of each el ment on each side of the arrow. This may be done by placing numbe *before* the appropriate formulas without altering the formulas and the significance. In balancing the equation it should be noted that two aton of oxygen are present on the left and must therefore be present on th right; this is achieved not by writing MgO_2, which is an incorrect formul but by placing 2 before the MgO. The two magnesium atoms on the rig require two on the left, and with this step the equation is balanced:

$$2\ Mg + O_2 \longrightarrow 2\ MgO$$

It is more important, however, to know the significance of an equation tha the mechanics of writing it. The quantitative meaning may be summ rized:

Equation:	2 Mg	+	O_2	$\longrightarrow$	2 MgO
	2 atoms		1 molecule (2 atoms)		2 molecules
Weight Relationship:	48.64 g		32.00 g	$\longrightarrow$	80.64 g

While an equation implies the above quantitative facts, it does *not* indicate the speed at which the reaction takes place, the extent to which it proceeds, nor the conditions under which the initial substances react. These facts may be determined experimentally, but may also be predicted to some extent on the basis of a knowledge of the properties of the substances and an understanding of chemical principles.

From a chemical equation the quantity of a substance reacting with or produced from a specified quantity of another substance may be calculated. For example: if one ton of coal, which contains 75 per cent carbon, is completely burned to give carbon dioxide, how much oxygen is consumed and how much carbon dioxide is produced? To solve the problem, the equation is first written, and the relative weights of the various substances indicated (approximate atomic weights are used):

$$C + O_2 \longrightarrow CO_2$$

$$12 + 32 \longrightarrow 44$$

This means that 12 parts by weight (grams, pounds, or tons may be used as long as the unit is retained throughout the problem) of carbon combine with 32 parts of oxygen to give 44 parts of carbon dioxide.

The amount of carbon in one ton of the coal is:

$$2000 \text{ lbs.} \times 0.75 = 1500 \text{ lbs.}$$

Since 12 lbs. of C require 32 lbs. of O_2, 1500 lbs. require $\frac{1500}{12} \times 32$ lbs. = 4000 lbs. of O_2.

Since 12 lbs. of C produce 44 lbs. of CO_2, 1500 lbs. of C produce $\frac{1500}{12} \times$ 44 lbs. = 5500 lbs. of CO_2.

It is the common practice of the chemical engineer or the experimental chemist to make such calculations before carrying out large or small-scale operations.

The Forces which Hold Atoms Together

The atomic theory has been shown to be the basis of modern chemistry. Its initiation by Dalton, who utilized quantitative methods, was followed by a period of research and refinement and by the development of the molecular theory. Gay-Lussac, Avogadro, Cannizzaro, and Berzelius, who introduced the use of symbols and made many atomic weight determinations, all contributed to the rapid development of chemistry in the nineteenth century. Parallel with this progress was the discovery of the electric current (Chapter 35), which was utilized in chemical research, and which later gave the key to the complex structure of atoms and the understanding of the forces which bind atoms together.

The term "chemical combination," used so often in this chapter, gives no clue as to the forces which cause atoms to combine and which hold them together in molecules. Various hypotheses have been formulated, but the solution of this problem came only after it was shown that the atom is a complex aggregate of electrical charges and neutral particles. Further discussion of atomic combinations must therefore be deferred until after electric charges and atomic structure are considered.

SUMMARY

1. The combustion of fuels, the rusting of metals, and the utilization of food in the bodies of animals are chemical changes which ordinarily involve union with oxygen.
2. In chemical changes, the initial substances disappear and new substances are formed, energy is either evolved or absorbed, the relative quantities of substances which react with each other are definite for a specific reaction under specific conditions, and there is no change in the total mass of matter involved.
3. The speculations of the early philosophers and the phlogiston theory of the alchemists were steps in the attempt to explain the phenomenon of combustion; the valid explanation was formulated by Lavoisier, who introduced quantitative measurement in the study of chemical reactions.
4. The first scientific atomic theory was introduced by Dalton, who assumed that all elements consist of atoms, all of which for a given substance are of the same average mass and are identical in properties, but which are different for different elements.
5. The atomic and molecular theories formulated to explain the law of definite proportions, the law of conservation of mass, and other quantitative data are used to interpret chemical changes.
6. Matter may be classified on the basis of the atomic and molecular theories:
   Mixture: consists of more than one kind of molecule.
   Substance: consists of only one kind of molecule.
   Element: a substance whose molecules contain only one atomic species.
   Compound: a substance whose molecules contain more than one atomic species.
7. Atomic and molecular weights are the relative weights of atoms and molecules, respectively, both with reference to the average weight of the oxygen atom, which is arbitrarily fixed as 16.0000.
8. A gram atomic weight of an element and a gram molecular weight of a substance contain 6.023×10^{23} atoms and 6.023×10^{23} molecules, respectively.
9. A chemical symbol denotes an atom of an element; a formula represents a molecule of a substance; and a chemical equation is a symbolic representation of a chemical change. All have quantitative significance.

STUDY EXERCISES

1. Before each phrase or statement write the letter:
   M, if the item refers to a mixture, *or*
   S, if the item refers to a substance, *or*
   B, if the item refers to both.
   .... is homogeneous.
   .... is heterogeneous.
   .... may be changed only by chemical means.
   .... all samples are the same in properties and composition.
   .... is of definite and constant composition.
   .... has mass.
   .... contains more than one kind of molecule.
   .... properties are an average of those of the components.

2. Before each phrase or statement write the letter:
   E, if the item refers to an element, *or*
   C, if the item refers to a compound, *or*
   B, if the item refers to both, *or*
   N, if the item refers to neither.
   .... is homogeneous.
   .... is heterogeneous.
   .... has a definite composition.
   .... has its own specific properties regardless of source or method of preparation.
   .... consists of only one kind of atom.
   .... contains more than one atomic species.
   .... contains more than one kind of molecule.
   .... may be chemically decomposed into simpler substances.

3. Indicate whether each change described below is chemical (C), or physical (P).
   .... A piece of copper dissolves with the evolution of brown fumes to form a blue-green solution when treated with nitric acid.
   .... A steel needle is attracted by a magnet but loses its magnetic property when heated.
   .... Moth "crystals" left in a closet gradually diminish in size and finally disappear.
   .... When vinegar is poured over baking powder, the latter dissolves and gas is given off.
   .... When water is poured over baking soda the latter dissolves.
   .... Eggs heated at 100° C. for five minutes become hard.

4. Each of the following elements is heated in the presence of oxygen. Complete the word equation and below this write the chemical equation for the combustion which takes place. The formulae for the respective oxides are CaO, Fe_3O_4, SiO_2, CO_2, and MgO. The formula for oxygen is O_2.
   (*a*) Calcium + oxygen ⟶
   (*b*) Iron + oxygen ⟶
   (*c*) Silicon + oxygen ⟶
   (*d*) Carbon + oxygen ⟶
   (*e*) Magnesium + oxygen ⟶

5. What facts led to the overthrow of the phlogiston theory? Assume that the proponents of the phlogiston theory insisted that phlogiston has a negative weight. What experiments would have to be performed to refute that argument?
6. Consult Table 32. On the basis of the atomic weights given, calculate the percentage composition of the following compounds:
   (*a*) Hydrogen oxide, or water, H_2O; (*b*) carbon dioxide, CO_2; (*c*) calcium oxide, or quick lime, CaO; (*d*) copper oxide, CuO; (*e*) red iron oxide, or hematite, Fe_2O_3.
7. How many grams of each of the following elements combine with two grams atomic weights of oxygen? (*a*) Carbon, (*b*) hydrogen, (*c*) calcium, (*d*) silicon, (*e*) iron.
8. (*a*) What is the number of atoms in 4 grams of oxygen? Calculate the actual weight of one oxygen atom.
   (*b*) How many molecules are present in 22 grams of CO_2? Calculate the actual weight of one carbon dioxide molecule.
9. List the significant differences between an atom and a molecule.
10. How many tons of iron could be obtained from 10 tons of an ore which is 80 per cent Fe_2O_3?
11. Summarize briefly the contributions of each of the following men: (*a*) Priestley, (*b*) Lavoisier, (*c*) Dalton.

FOR FURTHER READING

1. Hildebrand, Joel H., *Principles of Chemistry.* New York: The Macmillan Company, 1947
   An excellent book on the principles of chemistry. A very good discussion of matter and the principles of chemical changes will be found in Chapters I and II.
2. Conant, James B., "Combustion," *Readings in the Physical Sciences,* pp. 424–37. Harlow Shapley, Helen Wright, and Samuel Rapport, editors. New York: Appleton-Century-Crofts, Inc., 1948.
3. Pauling, Linus, *General Chemistry.* San Francisco: W. H. Freeman and Company, 1947.
   A discussion of elements, compounds, atoms, and atomic weights is found in Chapter IV. The meaning of symbols, formulas, and equations is discussed in Chapter VII.
4. Babor, J. A., and A. Lehrman, *Introductory College Chemistry.*
   Chapter 1 gives the rise of chemistry. A good discussion of chemical change and the atomic theory will be found in Chapters 2 and 3.
5. Briscoe, H., *Introduction to College Chemistry.*
   Chemical change is discussed in Chapter 2, and the modern atomic theory in Chapters 3 and 16.
6. Read, John, *Prelude to Chemistry.* New York: The Macmillan Company, 1937.
   This book is devoted entirely to alchemy and the transition of alchemy to chemistry. The outline and literature of alchemy are discussed in Chapters 1 and 2. Chapter 3 is devoted to the philosopher's stone.

23

The Nature of the Electric Charge

A VERY LONG TIME AGO, someone, either in the Orient or in Greece, found that a piece of amber rubbed with silk attracts bits of lint or similar small and light objects. The earliest record of this little fragment of knowledge, which represents the sum total of the ancient achievement in the field of electricity, indicates that this phenomenon was known to Thales about twenty-five hundred years ago. Two centuries later, Democritus (420 B.C.) proposed the theory that all matter is composed of individual atoms. This theory of matter and the phenomenon of electricity were handed down through the years as totally unrelated to each other, and stimulated neither experiment nor thought until comparatively recent times. That they are vitally related was not suggested until the last century and was not finally established until less than forty-five years ago.

If we recall the evolution of the atomic theory (Chapter 22) and trace in the present and next chapters the development of our knowledge of the nature of electricity, two important trends in science reveal themselves. The first is the gradual unification of what started out to be unrelated phenomena or different branches of science but later proved to be only different aspects of the same thing. To illustrate this trend, we have but to recall the falling apple and the motions of the planets or the kinetic molecular theory of matter and heat, and, to anticipate, electricity and matter. The second trend is also a natural and necessary one. Science begins with the most apparent phenomena which may be observed and studied without special technique and apparatus. It advances by the constant use of experiment and theory, and as this process continues the scope of science is extended. New theories suggest further experiments which may have to do with more subtle phenomena that in turn require new techniques and tools.

Astronomy was limited to observation by the naked eye until Galileo used the telescope for further observations suggested by the Copernican hypothesis. More powerful telescopes have been built and other special instruments developed, with the result that the astronomer has shifted his attention from the solar system to the stars and nebulae. The science

of mechanics was developed by study of the motions of visible and mov ble objects, like balls or rocks. It is now successfully applied to the m tions of very minute, invisible particles — molecules and atoms — as w as to celestial bodies. It has been shown that the chemist experimenti with gross matter made real progress only after Lavoisier introduc quantitative measurement. The laws which soon thereafter were form lated (Chapter 22) gave Dalton the experimental basis for his atom hypothesis. Order was thus introduced into chemistry, and both t chemist and the physicist, although continuing to work with quantiti of matter, began to think in terms of molecules and atoms. But it is n enough to resolve matter into elements and atoms. We must know t ultimate structure of the atoms themselves if we are to understand chem cal reactions and many of the physical phenomena. For this informati we return to the ancient experiment with the piece of amber.

The Greeks had small reason to investigate the charge on the amb It appeared to be an isolated phenomenon which had little to do with li and nature and was not associated with lightning or the electric eel, t only similar manifestations known to them. The picture today is ve different. The science of electricity leads us along two roads: first, to t development of the great electrical industry, which as a source of pow brings us into a new era with multiple changes in our way of life; an second, to a growing understanding of the structure of the atom and t nature of radiant energy. We shall, for the present, follow the seco road toward the problem of atomic structure. At the beginning we sh perform a few experiments which, without our goal in mind, might in the selves be neither new nor inspiring. The hypothesis by which we interpr our experiments is, however, of great significance.

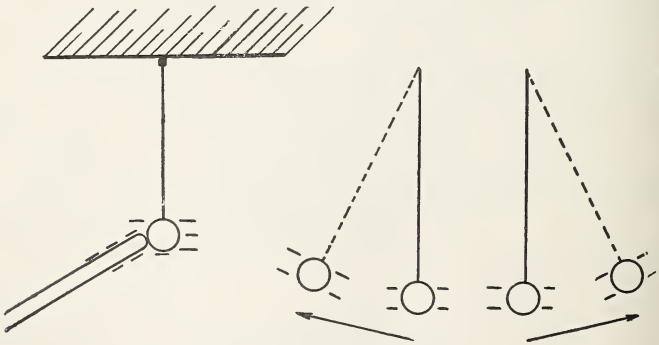


FIGURE 258

Pith balls charged by hard rubber rod which has been rubbed with wool or fur repel each other

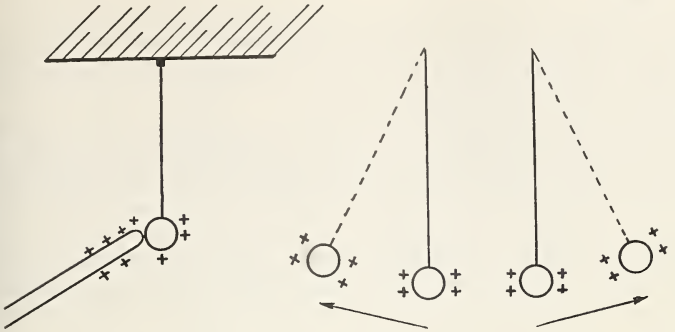


FIGURE 259

Pith balls charged by glass rod which was rubbed with silk repel each other

lectrification

First, we suspend two pith balls or inflated rubber balloons by silk ıreads. Next, we rub a hard-rubber comb or rod with a piece of woolen oth and quickly touch the comb or rod to one of the pith balls. This is peated with the second pith ball. In both cases the balls are repelled ter contact with the rod. If we now bring the balls close together they pel each other (Figure 258). Evidently the pith balls acquire something om the rod which causes them to behave in this way. That something e call electrification or electric charge. Since the two pith balls are both ıarged by identical methods, they must possess the same kind of charge.

Again, two pith balls are charged but this time by contact with a glass d which has been rubbed with silk. When brought near each other, the th balls mutually repel, just as they did before (Figure 259). As in the

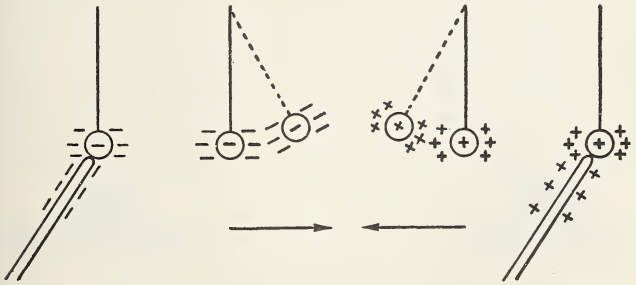


FIGURE 260

The pith balls charged by the rubber rod and by the glass rod, respectively, are mutually attracted

preceding experiment, we must conclude that, since both of the pith ball were charged by contact with the electrified glass rod, they again mus possess the same kind of charge. We conclude, therefore, that bodie carrying like charges repel each other.

Next, one of the pith balls is charged by the rubber rod and the othe by the glass rod. When brought near each other they are mutually at tracted (Figure 260). If we are to accept the above conclusion that lik charges repel each other, then we must infer from this experiment that th charge developed on the rubber is *unlike* the one on the glass, for the attract each other. Our findings may now be summarized: *Bodies carryin like charges repel each other, and those carrying unlike charges attract eac other.*

By trying other materials, such as sulfur, wood, and paper, we find tha many of them are easily electrified. Others, particularly metals, mus first be insulated from other metals or the earth. The first class of sub stances, on which the charge apparently does not easily move, are *non conductors*; the metals, over which the charge readily moves, are *conductor* The latter may be electrified if they are *insulated*, or separated from thei support by a non-conductor. In all cases the electrification is either lik that on the rubber (*resinous*) or that on the glass (*vitreous*). No thir kind of charge has been found.

Nature of Electrification

The experiments which have just been described led Dufay early i the eighteenth century to conclude that there were two kinds of electricit which, he implied, moved equally well through conductors. The resinou variety developed on the rubber or amber was designated as *negative* (− and the vitreous kind developed on glass as *positive* (+). Benjami Franklin, who was responsible for the positive-negative terminology, whic unfortunately is still in use, proposed a simpler one-fluid theory. Accor ing to this theory, all bodies contain the electric fluid, which is positiv if an excess is present, the body carries a positive charge; and if deficie in this subtle and weightless fluid, it carries a negative charge. The sim larity of this theory to the caloric theory of heat developed by Black i England at about the same time is striking. Either of the fluid theori explains satisfactorily the experiments in electrification if one can acce the idea of a weightless fluid and at the same time close his eyes to disco eries of the last forty-five years.

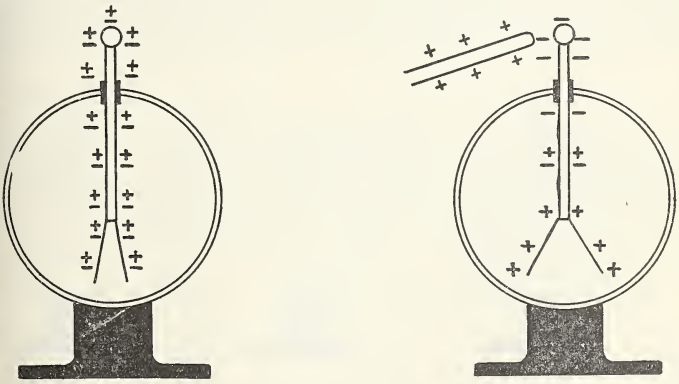
The year 1895 is now regarded as the turning point in the physic sciences, for beginning with that year a series of discoveries were mad that brought about very great changes in the theories of electricity an matter. These changes, leading to the modern theories of atomic structur will be discussed in the next few chapters. For the present it is sufficie to state that the electric "fluids" now appear to consist of positive an

egative particles and that these particles in turn are the very essence of natter. Experiments lead us to believe that the atom consists of these ositive and negative particles of electricity in equal numbers, and per- aps of neutral particles also. The negative particles, or *electrons*, appear o be more easily detached from their atoms, and, as we shall see a little ater, may even be isolated from matter. Evidence for these statements ill be forthcoming, and, as it is always a good test for a theory to apply to all related experimental facts, we shall begin with our simple experi- ents.

Friction, then, moves electrons from one body to another; the rubber od acquires electrons — and therefore a negative charge — from the wool, nd the silk removes electrons from the glass, leaving it with an excess of ositive particles. It follows that, if one body acquires a charge, some ther body acquires simultaneously an opposite charge of equal magnitude. Hence, the wool and the silk acquire positive and negative charges, re- pectively. If the glass is rubbed with the silk, the two bodies together how no charge, but if separated they show equal positive and negative harges, respectively. Charging the pith balls by contact becomes simply matter of transfer of electrons from the rubber to the pith, and we may milarly transfer electrons from the pith, which while neutral has an equal umber of negative and positive charges, to the glass.

lectrification by Induction

A second method of producing a state of charge may be effected without ntact between the two bodies. In this experiment an electroscope,



(*a*) (*b*)

FIGURE 261

) *An uncharged object consists of evenly distributed positive and negative charges.*
) *When rod bearing positive charge is brought near, electrons are drawn to upper part of electroscope, leaving lower part with excess of positive charge.*

which is a much more delicate detector of a charge than the pith ball, i used. The electroscope consists of two pieces of gold foil attached to metal rod and protected from air currents by a glass case or flask. Th rod must be insulated from the case by the use of a sulfur or rubbe stopper. When the electroscope is charged, the metal leaves fly apart for they acquire like charges. The glass rod with its positive charge i brought near the electroscope and the leaves fly apart; the rod is remove and the leaves go together again. It is evident that the charged bod influences the electroscope only when near it. The metal rod, knob, an leaves of the electroscope, like all other substances, consist of positive an negative particles in equal amounts (Figure 261, a). The approach of th glass rod with the positive charge attracts electrons to the upper part of th electroscope, and the leaves are left with a positive charge (Figure 261, b No charge leaves or enters the electroscope, and when the charged body removed, the electrons redistribute themselves and the leaves go togethe To charge the electroscope, electrons must either leave or enter it; this effected by "grounding" the instrument, that is, by simply touching th knob or by connecting it with some object which in turn is connected the earth. Applying this knowledge, we may now charge the electrosco by induction. The charged glass rod is brought near (Figure 262, a), an the finger or ground wire is placed for a moment on the knob, causing ele trons to flow into the electroscope from the body or the earth and thus ne tralizing the positive charges on the leaves, which collapse (Figure 262, b Meanwhile, the excess electrons on the knob are bound or held by the pos tive charge on the glass rod; when the rod is removed, they redistribu themselves over the electroscope (Figure 262, c), which is now negativel charged. By induction, therefore, the opposite kind of charge is obtaine

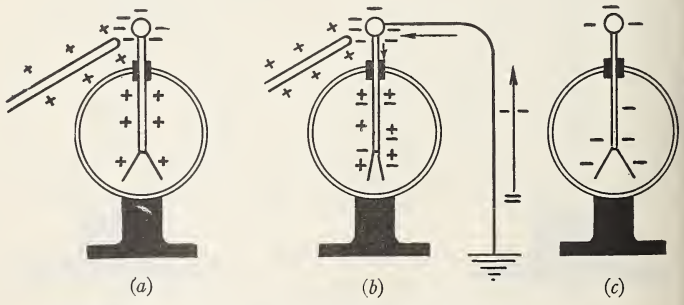


FIGURE 262. CHARGING AN ELECTROSCOPE BY INDUCTION

(*a*) *Electrons are drawn to knob by positive charge held near;* (*b*) *electrons from earth body neutralize positive charge on leaves;* (*c*) *electrons on knob distribute themselves ov entire system.*

Electrostatic Yardstick

The magnitude of the force of attraction or repulsion between two electrified bodies obviously depends upon the amount of charge on each and in some way upon the distance between the two bodies. Its exact value was determined experimentally in the latter part of the eighteenth century by Coulomb and formulated in what is known as Coulomb's Law of Electrostatic Charges. The law states: *The force of attraction or repulsion between two charged bodies is directly proportional to the product of the charges, and inversely proportional to the square of the distance between them.* Mathematically it is expressed:

$$F(\text{orce}) = \frac{Q(\text{uantity of charge})\ Q'(\text{uantity of charge})}{D(\text{ielectric constant})\qquad d(\text{istance})^2}$$

$$F = \frac{Q\,Q'}{D\,d^2}$$

The dielectric constant D depends upon the units used and upon the medium between the charged bodies; $1/D$ is therefore a proportionality constant. If the metric system is used, the value of D for air is approximately 1. This law is similar to the law of gravitation, but, whereas we have only a gravitational force of attraction, we have electrostatic forces of *attraction and repulsion.*

Coulomb's law defines the *electrostatic unit of quantity* of electricity. This unit is the charge which repels an equal and like charge at a distance of one centimeter in a vacuum with a force of one dyne (Figure 263). This is purely an arbitrary unit, but is of great importance, for upon it is based an entire system of electrostatic units. Electrical units, like all others, are derived units based upon the three fundamental units of measurement.

The Electric Field

The experiments described in the preceding sections call attention to a commonplace but very remarkable phenomenon, that of one electrified body exerting a force upon another at a distance. True, we have the similar sort of thing with magnets, and, in fact, the gravitational force is a constant operation between all particles of matter; but we are accus-

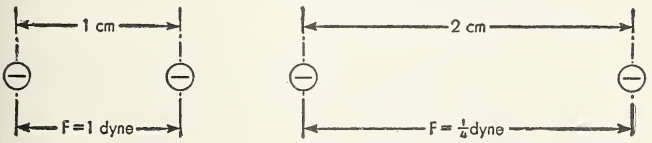


FIGURE 263

Identical unit charges placed 1 cm. apart repel each other with a force of one dyne; at twice the distance the force of repulsion is $\frac{1}{4}$ dyne (Coulomb's law).

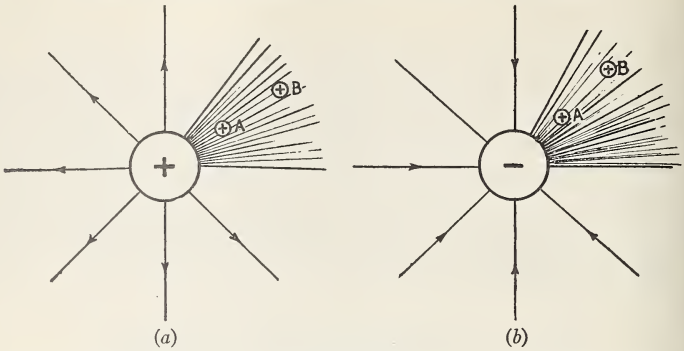
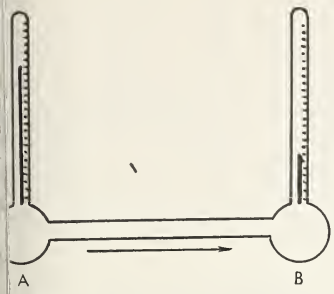


FIGURE 264
REPRESENTATION OF ELECTRIC FIELD AROUND CHARGED BODIES

tomed to observing such phenomena and to accepting them without asking why or how. In the region around an electrified body, electric forces are present and manifest themselves whenever another electrified body is brought into this zone. This region of influence is known as an *electric field*. The field concept was suggested by Faraday and put into mathematical form by Maxwell, both of whom we shall hear more about later. The existence of this electric force in space is not explained in terms of particles or waves or fluids. The field is in itself a concept, and it is definitely an aspect of electricity equal in importance to the concept of electric particles, if not greater. On the electrified body there is a charge which we interpret as an excess or deficit of negative particles of electricity; around the body in free space is the electric field. Both together constitute electricity. By convention the field is represented or described by lines which show at any point in the field the direction, and the number of them indicates the intensity of the force exerted on a small, positively charged body placed at that point. If we have a sphere which carries a positive charge, its field may be so represented by such lines (Figure 264, a). The force exerted on the small positive charge at any point A in the field may be read from the diagram. The force is that of repulsion (since like charges are involved) radially away from the center of the sphere, as indicated by the lines. If the charge is now moved to point B, which is twice as far away from the center as A, the lines are only one-fourth as concentrated or numerous in a given area, and the force by Coulomb's Law is only one-fourth as great. With a negatively charged sphere the field is similarly represented (Figure 264, b) except that the positive charge is attracted toward the sphere. In either case work is required to move the charge counter to the force of attraction or repulsion. The earth's gravitational and magnetic fields are represented by the same convention, ex



GURE 265. HEAT FLOWS FROM BODY HIGHER TEMPERATURE TO ONE OF LOWER TEMPERATURE

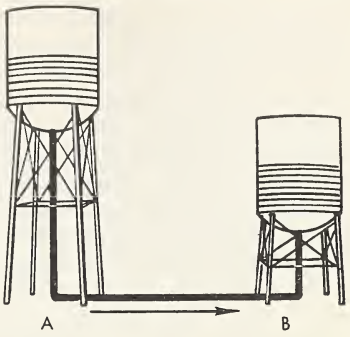


FIGURE 266. WATER FLOWS FROM HIGHER TO LOWER LEVEL

ot that in gravitation we have only attraction. The idea of so-called nes of force" grew out of this method of representation of the field.

e Concept of Potential

We observed in several of the experiments that electricity moves from e body to another. The charged rod gives some of its charge to the pith ll or to the electroscope when in contact with either of these bodies; a arged metal sphere may lose some of its charge to another body if con- cted to it by a conductor. There must be some reason for this "flow" of ctricity which suggests immediately the flow of heat energy from hot to ler bodies and the flow of water downhill from a higher to a lower level. As in all forms of energy, we have an intensity factor and a quantity tor. For heat (Chapter 20) the intensity factor, or temperature, is pressed in degrees; the quantity factor, in calories. Heat flows (Figure 5) from body A to body B irrespective of the quantities of heat in the o bodies as long as A is at a higher temperature than B. For the nmed-up water the intensity factor is the height through which it falls l upon which will depend the pressure it exerts. Water flows (Figure 6) from A to B, regardless of the quantity of water in the two tanks, as

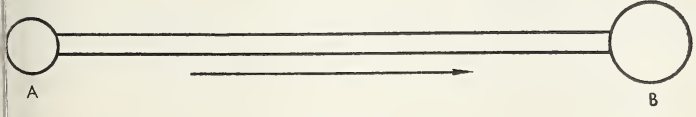


FIGURE 267

ufficiently high concentration of electrons on A may make for a potential difference een A and B. When joined by a conductor electrons move from A to B.

long as the level or pressure in A is higher than that in B. As for electricity the intensity factor which determines the flow of electrons from one bod to another is known as *potential* or *potential difference*. Electricity move from A to B (Figure 267) as long as there is such difference in the electro concentrations as to produce a difference in potential between the tw bodies. The two bodies may have like charges or unlike charges; they ma even possess identical quantities of charge. For example, the same tot charge may exist on A as on B, but the smaller body A as a whole has greater intensity or concentration of charge. Electrons more crowded t gether on one end repel each other with greater force and in a flash move t ward the other until the potentials are the same or potential difference zero.

It is apparent, then, that the electric potential bears the same relatio ship to temperature and to water level as the electric charge bears quantity of heat and to quantity of water respectively. If a flow of he is to be maintained between two bodies, one of them must be constant supplied with heat energy. If water is to continue to flow down from o level to another, a supply of water must be pumped by machines or l nature to the higher level. If electricity is to move through a conduct or across gaps, a higher potential must be maintained on one part of t circuit. In all cases work must be done, and in a later chapter we sha define our practical unit of electric potential, the *volt*, in terms of work.

Charged Conductors

We have already found that a conductor may be electrified provid that it is insulated from contact with other conductors. When a piece metal is charged by contact with an electrified body or an electrostat generator, the point of contact is momentarily at a higher, or lower, pote tial than the rest of the metal. The electricity, however, almost insta taneously distributes itself over the surface of the conductor so that t potential is everywhere the same. Although the potential is unifor over the entire body, the distribution of the charge is not, unless t body is a perfect sphere. If the body is not a sphere, then the char crowds in where the curvature is greatest, in order to maintain a unifor potential. The charge around the point of the metal rod (Figure 268) much more concentrated than on any other part of it. At such a poi of high concentration the charge tends to escape to the air molecules contact with it. As the charged air particles are repelled, the effect

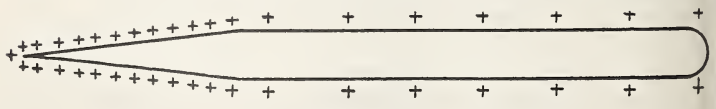


FIGURE 268

On a metal conductor the potential is uniform but the charge is concentrated at points

o discharge the point and set up an air current or so-called electric wind. ince the charge is always distributed over the surface of the conductor, he inside of a charged metal container should be free from any electric ffects. Faraday carried an electroscope into a large box coated with ietal foil and placed on an insulated stand. He could find no evidence f electrification within the conductor, although the box was strongly elec- ified from the outside. Nor does the container have to be solid. An lectroscope placed in a wire mesh box or cage is not affected by the passage f electric sparks to the cage. It is frequently necessary to protect in- ruments, vital parts of radio sets, explosives, or cable stations by so creening them from outside electric effects. The electric field does not et any farther than the surface of the conductor, unless, of course, a charge carried into, or generated within, the screened space.

The inside of a metal cage, of an all-steel home, or of a modern sky- craper with its structural steel framework is a safe place during *electric orms*. The *lightning rod*, if properly installed, well grounded, and with iarp points, affords very good protection. That lightning is an electro- atic phenomenon was first proved by Benjamin Franklin, who, by means f a kite sent up during a thunderstorm, drew sparks from a thunder-cloud, sing a key at the end of the wet kite-string — a very dangerous experi- ient. He also charged a Leyden jar (a condenser — see below) by in- uction from the clouds. During the fall of rain the drops may be broken p into droplets and mist which acquire an electric charge in the process. louds thus become charged and induce other charges on neighboring ouds or the earth. A low cloud bearing a positive charge will induce a

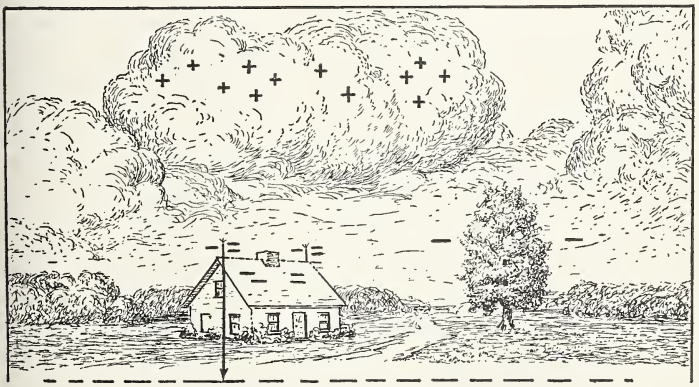


FIGURE 269

The charge induced on the house leaks off at lightning rods, thus preventing spark discharge or lightning; in case of a direct hit the rod serves as a path for the discharge.

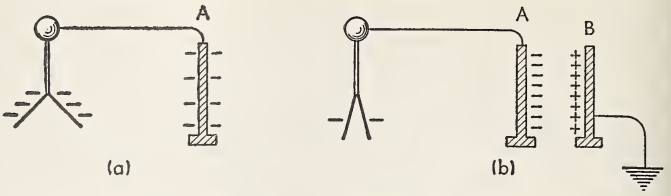


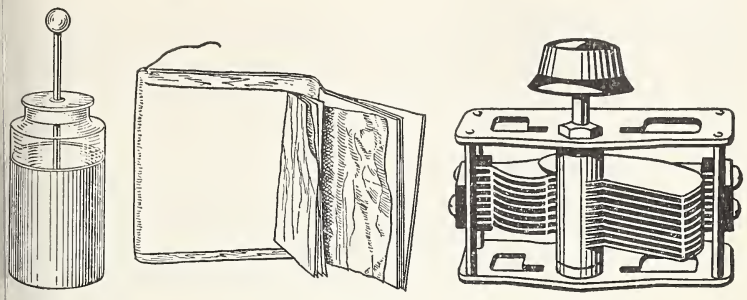
FIGURE 270. CONDENSER
The presence of the grounded plate increases the capacity of A

negative charge on the earth (Figure 269). Since the two charged bodie the cloud and the earth, are separated by the air, which tends to keep th opposite charges apart, a considerable potential may be built up betwee the two. If the potential becomes great enough, the air may become ion ized and then a great discharge occurs as lightning. A house equipped wi a lightning rod is protected in two ways. The electricity leaks off escapes at the points of the rods, thereby preventing the building up of sufficiently high potential for the lightning discharge. Or, in case of direct hit, the rod conducts the electricity harmlessly to the earth.

Condensers

The arrangement pictured in Figure 269 — cloud, air, and earth constitutes what is known as a *condenser*. This natural condenser is on grand scale, but smaller ones are manufactured and have importa uses. A condenser consists essentially of two conductors, one of which grounded, separated by a medium known as a dielectric which keeps th charges apart. The purpose of a condenser is to increase the ability of conductor to hold electricity, or, in more scientific language, to increa its *capacity*. The metal plate A (Figure 270, a), which is mounted on a insulated base, may be charged and the potential indicated by an ele troscope connected to the plate. If another plate, B, which is grounde is brought near A, the electroscope leaves fall, showing a decrease i potential (Figure 270, b). The second plate is charged by induction, an the bulk of the charge on A is drawn to the face near to B. A muc greater charge may be added to A before the leaves of the electrosco diverge to their former positions. Therefore, the condenser permits much greater charge for a given potential.

Glass, or some other substance with greater dielectric properties tha air, placed between the plates increases the capacity. Larger plates gi proportionally larger capacities; moving the plates closer together gives further increase. These principles are utilized in the design of commerci condensers. The Leyden jar consists of a glass vessel coated to more tha half of its height, inside and out, with metal foil (Figure 271, a). Othe consist of alternate layers of metal foil and oiled paper or mica, with th



(*a*) (*b*) (*c*)

FIGURE 271. VARIOUS CONDENSERS

(*a*) *Leyden jar;* (*b*) *tinfoil, oiled paper condenser;* (*c*) *radio condenser*

lternate sheets of metal connected together (Figure 271, b). Such an ar-ıngement gives in effect large surfaces very close together with resultant igh capacity. For the automobile, the condenser is often made of two ıng strips of tin or other metal foil separated by oiled paper and folded ɔ that it may be inserted in a waterproof case of small volume. The tuning" knob on a radio receiving set is connected to a condenser con-sting of two sets of metal plates with air between (Figure 271, c). Turning ıe knob moves one of the series of plates (the other is stationary) in be-veen or away from the blades of the other, thus varying plate areas ɔposite each other and consequently the capacity.

ıe Atomic Theory of Electricity

We have seen that the electric charge may be generated by rubbing ertain materials with others, such as glass with silk or amber with wool. ı order to explain such electrification we have assumed that negative ırticles of electricity, called electrons, are transferred from one body to ıother. This hypothesis is applicable to all types of electrostatic gen-ɛrators from the amber of the ancients to modern machines. But agree-ent with fact does not warrant acceptance of an hypothesis if the facts ɛ explained equally well by other hypotheses. The facts examined so ır do not exclude, for example, the possibility of positive mobile charges ɛ even of a continuous electric fluid. In none of the experiments which ıve been discussed has the electric particle or fluid been segregated from ıe rest of matter. In the next chapter, however, we shall consider ethods whereby beams of electrons may be isolated, studied, and utilized, dicating that matter is composed of these and other particles.

Even before these methods were discovered, the atomic or particulate ıture of electricity was anticipated. Helmholtz in 1867 and later John-

stone Stoney pointed out that the atomic theory of matter and the law of electrolysis (Chapter 37) indicate that there must be a fundamental unit of charge. After the isolation and discovery of the electron, this fundamental unit of charge was measured by a very ingenious method.

The Charge of an Electron

The determination of this minute charge — one of the fundamental constants of nature — is a remarkable achievement of both theory and experiment. As the individual electronic charge is too small to be isolated and observed, it was necessary to deal with larger and measurable aggregates of matter, most of them bearing many of the unit charges. If a sufficient number of measurements of the total charge borne by each of a number of small bodies is made and if the charges are varied and measured each time, the highest common factor of all the different total charges should be the value sought.

It was by such methods of reasoning that experimental procedures were developed, first by J. S. Townsend, Rutherford and Geiger, J. J. Thomson and others, and later by R. A. Millikan (1914–17) at the University of Chicago. Millikan used droplets of oil sprayed from an atomizer in the space between electrically charged plates, some of the drops being charged by friction. Individual charged drops were observed as they fell due to the pull of gravity, but their rate of fall could be controlled, stopped, or even reversed by regulation of the electric field between the plates. Under the influence of a beam of X-rays some of the molecules in the air become electrically charged and by collision with an oil drop may bring about a sudden change in the magnitude of the charge of the latter. When this occurs the oil drop suddenly changes its velocity — its movement becomes faster or slower. Sufficient data were collected from hundreds of obser

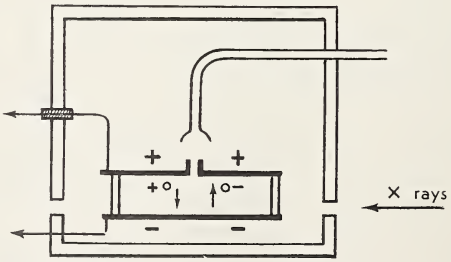


FIGURE 272. MILLIKAN'S OIL DROP EXPERIMENT IN WHICH THE FUNDAMENTAL ELECTRIC CHARGE WAS MEASURED

vations to permit the charge on each drop to be calculated. This method was modified in 1941 by Hopper and Laby who intermittently illuminated and photographed the drops as they fell and diverted them by an electric field between vertical plates. The value obtained for the fundamental charge, of which all of the drop charges were whole number multiples, was 4.802×10^{-10} electrostatic units. This quantity may also be expressed in coulombs: $4.802 \times 10^{-10}/3 \times 10^{9}$ (a conversion constant) $= 1.601 \times 10^{-19}$ coulombs. The charge of the electron may be used to calculate the value of Avogadro's number (see page 422) from the relationship $F = Ne$, where F is the value of the Faraday (see page 676) in coulombs and e the fundamental charge. From the above equation,

$$N = \frac{F}{e} = \frac{96{,}487.7}{1.601 \times 10^{-19}} = 6.023 \times 10^{23}$$

the number of molecules in 1 mole.

SUMMARY

1. There is a trend toward unification in science, especially of the theories of matter and of those of electricity. Such a unification does not necessarily imply simplification.
2. There is a forward trend in science — new techniques, new instruments, and new understanding.
3. Electrical charges may be developed by friction on a nonconductor or on an insulated conductor.
4. There are two kinds of electrification which are called negative or resinous and positive or vitreous.
5. Bodies bearing like charges repel each other and those bearing unlike charges attract each other.
6. An object may be electrified by direct contact with a charged body receiving the same kind of charge; or it may be charged by induction, when it acquires the opposite kind of charge. In both instances electrons are transferred from one body to another or to the earth.
7. Coulomb's Law states that charged bodies attract or repel each other with a force which is proportional to the product of the charges and inversely proportional to the square of the distance between them. Note similarity to law of gravitation.

8. The fundamental electrostatic unit of charge is that charge which will repe an identical charge one centimeter away with a force of one dyne.
9. An electric field is the region around an electrified body in which electri forces are present. It is a fundamental aspect of electricity.
10. Potential is the electrical intensity factor analogous to water pressure and t temperature.
11. A charge distributes itself over the surface of a conductor so that all point on the surface are of equal potential. At regions of greatest curvature ther is a maximum concentration of the charge.
12. The fact that a charge resides on the outside surface of a conductor make possible electric shielding.
13. Lightning is due to induction and the building up of an enormous charge o a natural condenser.
14. A condenser, essentially two conductors, one grounded, separated by a di electric, increases the capacity of a conductor and permits the accumulatio of a greater charge for a given potential.
15. The hypotheses that all matter is composed of particles of electricity an that the negative particle or electron is transferable serves to explain th facts of electrification. The measurement of the fundamental unit of charg by Millikan and others points to the atomic character of electricity.

STUDY EXERCISES

1. Describe with the aid of drawings how one may demonstrate with home made apparatus that unlike electric charges attract and like electric charge repel each other.
2. Using the same apparatus, show how one may demonstrate that there ar two kinds of electric charges.
3. A rubber rod is rubbed with wool, and the two are kept together and brough near the knob of an electroscope. Explain the result. The rod is now re moved from the wool and held near the electroscope. Explain.
4. Using a drawing, describe how an electroscope may be given a positive charg by induction.
5. (*a*) Two charged bodies placed 3 cm. apart in air attract each other with force of 12 dynes. One of the bodies carries a positive charge of 4 electro static units. What is the magnitude and kind of charge on the othe body?
   (*b*) The bodies are now placed 6 cm. apart. What is the force of attractio between them?
6. Fill in the blank spaces of the table with a word or statement that corre sponds to the one given for dammed-up water.

Dammed-up Water	Heat	Electricity
(*a*) Water level		
(*b*) Height through which water falls		
(*c*) Quantity of water		
(*d*) When dam is opened, water flows until levels in lake and stream into which it flows are same		
(*e*) To start flow, water must be carried to higher level, i.e. work done		

Explain the development of a negative charge on a piece of rubber by each of the following hypotheses:

(*a*) The two-fluid hypothesis.

(*b*) The single-fluid hypothesis of Franklin.

(*c*) The modern electron theory.

Compare the force of gravitation with the forces exerted by electrically charged bodies, by checking in the appropriate blank if the statement is true of either or both phenomena.

	Gravitation	Electric Charges
(*a*) Exerts force of attraction		
(*b*) Exerts force of repulsion		
(*c*) Obeys inverse square law		
(*d*) Fields or zones of influence exist around the bodies exerting such a force		
(*e*) The force is exerted by every particle of matter		
(*f*) Requires work to develop		
(*g*) Force may be demonstrated only with bodies of great mass		
(*h*) Work is required to move a body against the force		

Check each statement or phrase which correctly completes these sentences. There may be more than one correct answer.

(*a*) The capacity of a condenser is increased by:

.... increasing the size of the metal plates.

.... moving the metal plates further apart.

.... using a stronger dielectric or non-conductor between them.

.... using more metal plates with alternate ones connected together and between them non-conductors.

(*b*) A safe place in an electric storm is:

.... under a tree.

.... in an automobile with a metal top and body.

.... in a steel and concrete building.

(*c*) On an irregular metal surface which is insulated and electrically charged:

.... all points have the same potential.

.... the charge is evenly distributed over all parts of the uneven surface
.... the charge is greatest where there are sharp bends or points in the metal.

(*d*) A man in a metal wire cage holding an uncharged electroscope and sitting in an insulated chair, may charge the electroscope by:
.... having electric sparks discharge on the outside of the cage.
.... connecting the cage to a battery.
.... rubbing his comb against his wool coat and touching to the electroscope knob.

10. What single bit of evidence, discovered before 1850, indicated that electricity was atomic rather than a continuous fluid?
11. Suppose that Millikan had found that one of the oil drops carried a charge of 7.16×10^{-10} electrostatic units. How would that fact have changed his conclusion as to the value of the fundamental charge?
12. Write a brief explanation of each of the following (give illustrations or make drawings where necessary):
(*a*) Often phenomena which appear to be unrelated prove later to be different aspects of the same thing.
(*b*) One cannot charge a metal rod by holding it in the hand and rubbing it.
(*c*) "Lines of force" are not real lines that reach out and act on other bodies.
(*d*) All points on the surface of a charged conductor have the same potential.

FOR FURTHER READING

1. EYRING, C. F., *A Survey Course in Physics.*
Chapter XV provides an introduction to electricity and magnetism that the student with little or no science can understand.

2. ROBERTSON, JOHN K., *Atomic Artillery and the Atomic Bomb.* New York: D. Van Nostrand Company, Inc., 1945.
An interesting little book written in non-technical language on the most fascinating subject of modern science — the electrical nature of matter. It demands nothing of the reader but an "intelligent interest." Chapters I, II, and III give a review of atomic theory and introduce the electric charge, the concept of potential, and electrons.

3. LEMON, H. B., *From Galileo to the Nuclear Age.*
Chapters 19, 20, 21, and 22 are brief but well-written and entertaining chapters on the electrostatic charge, conduction, induction, and thunderstorms.

4. BRAGG, W. L., *Electricity.* New York: The Macmillan Company, 1936.
This book consists of the popular Christmas lectures given at the Royal Institution in London for younger students who have little knowledge of physics. Chapter I deals with electrical charges, fields, potential, condensers, and the nature of electricity. First-class drawings, descriptions of unusual experiments, and the clear style make this one of the best books for the beginning student.

5. TAYLOR, L. W., *Physics, the Pioneer Science.*
In Chapter 40 the author discusses static electricity and gives a good explanation of the condenser.

6. Millikan, Robert A., *Electrons (+ and −), Protons, Neutrons, Mesotrons, and Cosmic Rays.* Chicago: The University of Chicago Press, 1947.

Chapters I, III, IV, and V present early views of electricity and attempts to determine the value of the fundamental charge, followed by a discussion of the atomic nature of electricity and the author's more exact determination of the fundamental charge. This book is for the better prepared student.

7. Cohen, Bernard (editor), *Benjamin Franklin's Experiments.* Cambridge, Massachusetts: The Harvard University Press, 1941.

Franklin's letters and experiments on electricity for those who are interested in America's first great scientist.

8. Stranathan, J. D., *The "Particles" of Modern Physics.* Philadelphia: The Blakiston Company, 1942.

In Chapter 2 the various methods for the determination of the electronic charge are discussed.

24

The Electrical Nature of Matter

WE HAVE FOUND that there are two kinds of electric charges which, by convention, are called *positive* and *negative*. These two kinds of electricity attract each other, and each is repelled by its own kind, in accordance with a law which we recognize to be similar to the law of gravitation. These forces of attraction and repulsion and the methods of communicating a charge to other bodies introduce us to the concept of the electric field which, as an integral aspect of electricity, always accompanies the charge and is of great importance in modern science. The study of static electricity, while affording a good testing ground for the hypothesis of the electron, does not present positive evidence for the atomic nature of electricity, nor does it indicate which, if either, of the charges is more easily transferred from one body to another. As long as studies in this field were confined to charges on solid bodies or the flow of current in other solid bodies (conductors), the fundamental questions about the nature of electricity remained unanswered.

On the other hand, experiments on the passage of the electric current through liquid conductors led to the inductions known as Faraday's Laws of Electrolysis (Chapter 37) As mentioned in the preceding chapter, a few scientists read in these laws evidence for the atomic nature of electricity. But most productive of all were the investigations on the passage of the electric current through gases, through the air, and at various reduced pressures, which, together with the discovery of radioactivity, yielded decisive data on which the modern theory of matter and electricity is built. Under many different circumstances and conditions, negative particles of electricity have been segregated from bulk matter and studied. Electrons stream from the cathode regions of highly evacuated tubes through which the electric current is passing; they are spontaneously hurled from the interior of the atoms of radioactive substances; they are driven out of metal wires by heat; they are ejected from certain substances illuminated by X-ray, ultra-violet, and even visible light. *In all of these instances the negative particles are found to be identical.*

Practically every one of these great discoveries was prompted by man's

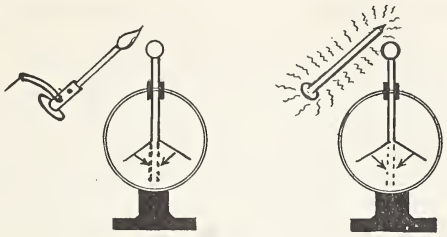


FIGURE 273

A charged electroscope is discharged when a flame or hot metal is brought near it.

esire to know and to understand, rather than by the urge to produce omething useful. Geissler, Crookes, and Thomson were not trying to uild X-ray tubes or neon signs; nor were Becquerel and the Curies seeking treatment for cancer or a way to illuminate watch dials. Yet all of these iscoveries have proved to be of great practical value to health, to industry, nd to our general culture. For the present we shall discuss more thor- ughly those discoveries which point directly to an understanding of the ature of matter, and in a later chapter those which reveal, in addition, ıe nature of the electric current.

\ir as a Conductor

Air under ordinary conditions is a poor conductor of electricity. When e flip the switch which opens the circuit to the lamp or vacuum cleaner, e do so on the assumption that electricity will not flow through the air cross the open gap. For the same reason an electroscope which is well ısulated and charged retains its charge for some time. If we wish elec- icity to flow in the lamp circuit, we close the gap with a metal conductor; we wish to discharge the electroscope instantly, we touch the knob with ır finger or with a grounded metal conductor. Yet there are circum- ances under which electricity will traverse the air or other gases through ıe gap between two wires or terminals, and there are similar or other rcumstances under which the electroscope may be quickly discharged the air.

Even with the most careful insulation the electroscope will very slowly se its charge. But a flame or a white hot piece of metal — iron or plati- ım, for example — held near but not touching the electroscope brings out a rapid discharge (Figure 273).

Ultra-violet light, a considerable amount of which is in sunlight but which artificially obtained from the mercury-in-quartz or the carbon arc lamp, ings about a rapid discharge. X-rays, which are best known for their e in medical photography and treatment and which are light waves of ry high energy, produce an immediate discharge. In addition, certain

elements which are known as radioactive and which will be discussed in this and the next chapters, produce a similar effect. How do these varied and unrelated phenomena all bring about the same effect?

According to the kinetic molecular theory (Chapter 20), the air and all other gases consist of molecules in a constant state of random motion. The molecule is a neutral particle and as such plays no part in the discharge of the electroscope. Under the influence of any of the agents mentioned above, some of the gas molecules in the air lose electrons and are left with positive charges; others pick up one or more electrons and thus acquire negative charges. The molecules, atoms, or groups of atoms which have acquired electric charges are called *ions* (or wanderers). The ionizing agents bring about this important phenomenon in a variety of ways. The energy of the chemical reaction which produces the flame may result in an unequal distribution of electrons — an excess on some molecules and a deficit on others, i.e., ionization. Radioactive substances hurl into the air both positive particles and electrons and emit a radiation even more active than X-rays. The rapidly moving particles plow through the air, knocking off electrons here and there, and these negative particles in turn may attach themselves to other molecules. The effect of the hot body and of the radiation will be discussed more completely in a later chapter. The assumption of the existence of a transferable negative particle — the electron — serves to explain ion formation in any case. Hence, in the air around the charged electroscope are swarms of ions, positive and negative, all moving rapidly. Some of the ions approach the knob or leaves and are attracted by the opposite charge. If the electroscope holds a positive charge, it is neutralized by the negative ions which it attracts when they pass near by and from which it takes electrons. If the electroscope holds a negative charge, it may give electrons to the positive ions which come into contact with it. (See Figure 274.) The result is a discharged electroscope and a loss of charge by the ions. In any gas, only

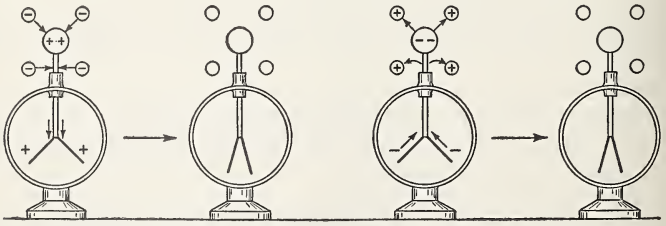


FIGURE 274

An electroscope with a positive charge may receive electrons from the air or from negative ions in the air; one with a negative charge may give electrons to positive ions in the air. The result is loss of charge by the ions and by the electroscope.

a small fraction of the total number of molecules is ionized, and the ions soon disappear when the ionizing agent is removed.

The charge on the electroscope, however, slowly leaks off even in the absence of any of the ionizing agents which we have discussed. The electroscope may be well insulated, shielded from light, and surrounded by air which has been very carefully cleansed of ions by passage through closely packed glass wool or water. Yet there is a slow discharge. Some agency must cause this very slight ionization of the air — for a few ions are always present. For some years scientists attributed their presence to traces of radioactive material in the earth or air. To test this hypothesis electroscopes were set up on ships at sea and on frozen lakes and were even sent up into the upper atmosphere by balloons. It was found that the discharge continued and actually increased at high altitudes. The radiation which causes this effect must, therefore, come to the earth from outer space and is appropriately called *cosmic radiation*. More will be said later about this interesting but mysterious energy whose origin is not known and whose nature is not clearly understood. It is now being investigated on a worldwide scale.

Spark Discharge

For an electric discharge to take place between two clouds or between any two conductors, there must be, first, a difference of potential; and secondly, there must be some sort of conductor between the points of discharge — a metal, a solution, or an ionized gas. We shall consider at this time, as in the preceding section, only conduction by gases. Where there is a difference of potential an electric field exists, and ions move in that field in accordance with the law of attraction and repulsion. (See figure 275.) An ion, C, bearing a negative charge, or even a free electron, will move from A to B, being repelled by A and attracted by B. The speed with which it moves through the air or gas increases with the difference in potential between A and B. Its motion is also retarded by numerous collisions with molecules and other ions. We may recall how Millikan regulated the motions of electrified oil drops by a careful control of the field in which they moved. Electrified particles are accelerated to enormous velocities by the use of extremely high potentials just as bodies falling from great heights are accelerated to very high velocities.

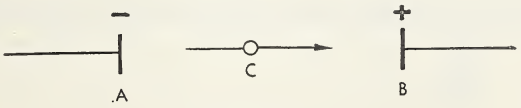


FIGURE 275

An ion or electron moves in the field between two charged plates with an acceleration which increases with an increase in the potential difference between the plates.

As the potential difference between A and B is built up, no discharg across the air gap is apparent except, possibly, a slight glow, until a certai very high value (thirty thousand volts per centimeter or, with pointe terminals, considerably less) is reached. Then in a fraction of a second a spark leaps across the gap with a crackling noise, and the potential drops unless restored by work done on an electrostatic generator or by electri energy supplied to a spark coil. In this brief moment of flash and dis- charge, many things happen — the phenomenon is extremely complex. Yet we can give a general picture of how the spark discharge occurs. To start with, there must be a few ions present in the air. These ar accounted for by one or more of the ionizing agents mentioned earlier A positive ion is formed when a molecule loses one or more electrons which may or may not at once attach themselves to other molecules t form negative ions. The ions and electrons move swiftly under the in- fluence of the field and, smashing into the air molecules, knock electron from these, forming more ions and freeing more electrons. The latter due to their extremely small mass, move with great speeds many time those of the ionized air particles, which have the same kinetic energy ($\frac{1}{2}\ mv^2$). The electrons plowing through molecules free more electron and form more ions. The action multiplies, and soon there is a path o charged particles across the air gap. Repulsions and recombinations tak place, between both electrons and ions, at the plates and in the space be tween. Atoms glow, for within them electrons vibrate; and it all ends wit the spark and crash. The energy of the electricity is converted into light heat, and sound.

The electric discharge is useful as well as spectacular. It fires our auto mobile engines and, when quieted down, gives a luminous glow which w see in neon and other similar lights; but, most important, it gives us crucia information about the nature of matter.

Discharge at Low Pressures

While the air in the gap between the plates yields by collision the ion and electrons necessary for the passage of electricity, it is nevertheless a obstacle to the rapid and free passage of the charged particles. If th

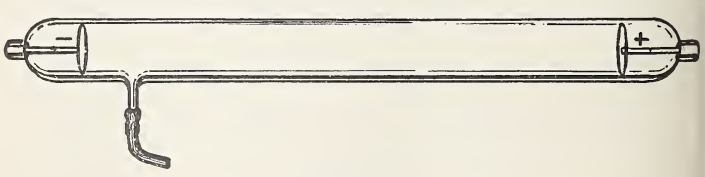


FIGURE 276

Discharge takes place more readily and quietly between two electrodes when air is removed from the gap between them.

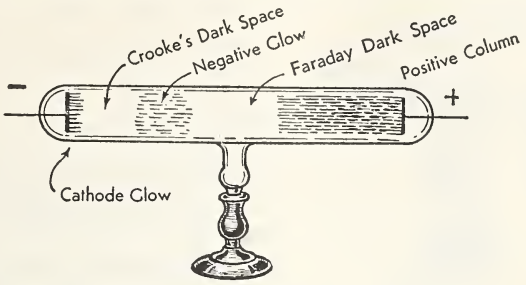


FIGURE 277

As tube is evacuated more and more alternate regions of glow and darkness appear.

ates, which we may now call electrodes, are sealed into a glass tube and e air gradually pumped out, the discharge appears to change progres-ely. The electrodes (Figure 276) are connected to a spark coil, and the e arm of the tube to a vacuum pump. When the pressure is reduced about ten millimeters of mercury (1/76 atmosphere), bluish ribbon-like eamers of light silently flash through the tube. As the pressure is ther reduced the streamers give way to a reddish glow which fills the be. This breaks and recedes toward the positive electrode (*anode*), and bluish luminous glow appears around the negative electrode (*cathode*) h alternate regions of light and dark spaces. (See Figure 277.) Finally, when the pressure is reduced to one one-hundred-thousandth that of the atmosphere, the zones of light disappear, the glass glows with greenish light, and a faint streak of light may be discerned extending m the cathode. This ray has been the object of much study. Some of e early investigators thought it to be a beam of light. The vacuum-charge technique was developed by Geissler in Germany and Crookes England, and a thorough study of these *cathode rays* and related phe-nena was made by J. J. Thomson at Cambridge University. Some of ir conclusions may be verified by the observation of the cathode-ray charge in special tubes.

thode Rays

These "rays" cast well-defined shadows on the wall of the tube opposite the cathode (Figure 278). Though the rays are scarcely visible, their pact on the glass is evident from the greenish light which they cause glass to emit. Something in the glass receives the rays or radiation l gives off visible light. This phenomenon is known as *fluorescence* and mits us to see the shadow cast by an object placed in front of the cath-. We may therefore conclude that cathode rays actually emerge from cathode and normally travel in straight lines.

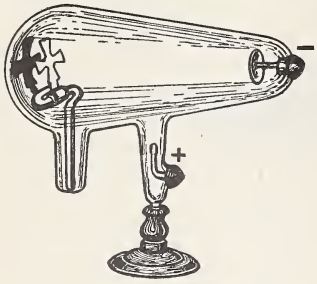


FIGURE 278

A shadow cast on the wall of tube opposite the cathode proves that cathode rays come from the cathode and move in straight lines.

The cathode rays are deflected c bent from their straight-line path by magnetic field (Figure 279) and by a electric field. After some difficult Thomson finally demonstrated the de flection by an electric field, but th was only after he had placed the fiel plates within the tube. The defle tion was toward the positive an away from the negative plate. It was shown by Perrin (1895) that th rays gave a negative charge to a de icate measuring instrument upon whic they were deflected. Cathode ray therefore, consist of a stream of neg tive particles — electrons.

From the amount of deflection in a field of known strength, Thomso obtained a value for the charge-mass ratio e/m. From this figure an the value for e (see Chapter 23), m, the mass of the electron, was ca culated to be 1/1850 of that of the hydrogen atom. Since it consists particles in motion, the electron stream possesses mechanical energy. small paddle wheel is rapidly rotated when the cathode rays are directe on the paddles (Figure 280). The cathode rays pass through very th sheets of aluminum foil, but, when directed against a thicker piece of heavy metal, such as platinum, they heat it to redness (Figure 281). Th velocity of the electrons depends on the potential difference between th electrodes of the tube. For a potential difference of one hundred thousa

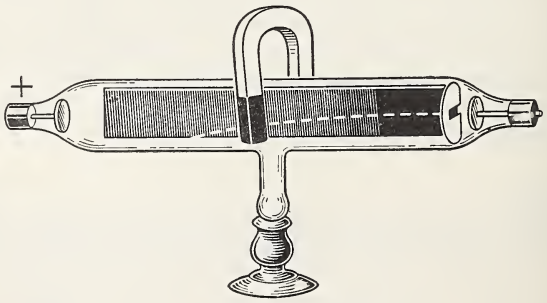


FIGURE 279

Cathode rays passing through slit in front of cathode are visible against background fluorescent material and are deflected by magnet in such a way as to indicate that they con of negative particles.

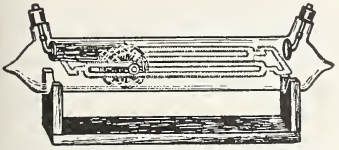


FIGURE 280

Cathode rays possess kinetic energy. When directed against paddles of wheel they cause it to rotate.

FIGURE 281

Cathode rays striking metal foil raise its temperature to red heat.

lts the speed is over one hundred thousand miles per second, and such electron beam possesses a great quantity of energy.

To sum up: In a slightly reduced pressure the discharge resembles somehat that of the spark. As more of the air molecules are removed, all rticles move more freely. Positive ions strike the cathode with sufficient ergy to set free electrons which, under the high field, move swiftly until ey strike ions or molecules or the anode. At that stage of evacuation, hich gives the dark and light spaces, the electrons evidently traverse e dark spaces, acquiring enough energy to cause ionization of the gas the regions of glow. As energy is absorbed to produce ionization, so ergy is emitted by recombination of electron and ion, producing the glow. the final stage of the evacuation there is no glow. The beam consists marily of electrons; but gas molecules are essential, as is shown, first, by e fact that further evacuation arrests the discharge and, secondly, by e existence of positive ions, which move toward the cathode. (See ge 459.)

Thomson carried out a series of experiments with cathode rays in which used different materials for cathodes and a variety of gases in the tube. all cases he obtained the same stream of negative particles (the same lue for e/m). Here, for the first time, we have definite evidence that e electron is a fundamental constituent of all atoms.

e Discovery of Natural Radioactivity

The studies described in the previous section, which led to the discovery the electron, initiated two other discoveries of equal importance, those X-rays and radioactivity. These three discoveries, all made within a riod of three years, are said to mark the beginning of modern physical

science. The X-rays which Roentgen found in 1895 to be given off fro a cathode ray tube and which passed through glass and many opaq objects, yet which could not be seen, aroused world-wide interest. As th appeared to spring from the part of the tube where the cathode rays stru and produced fluorescence, they were at once associated, in the minds scientists, with this phenomenon. Investigations were made of ma substances which show fluorescence and also phosphorescence to see if the too, emit similar rays, which, for example, affect a photographic pla through black paper.

Henry Becquerel, in Paris, investigated the properties of a number *phosphorescent* substances. These materials, after illumination wi X-ray, ultra-violet, or visible light, continue to emit light ordinarily different wave length from that absorbed. Becquerel found that, of of the substances he tried, only salts of uranium gave a photographic effe through the black paper. He tried further experiments in which he us the uranium compound after it had been kept in darkness for days so th there was no phosphorescence, and he obtained the same results. Th indicated that uranium normally emitted whatever affected the phot graphic plate. It was also found that this radioactive property was spo taneous and could not be controlled in any way. Thus *radioactivity* w discovered, and in an element which had been known for more than o hundred years. Evidently no one up to that time had observed its effe on a charged electroscope.

The work initiated by Becquerel was carried on by Pierre Curie and h wife, Marie Sklodowska, who found that the ore pitchblende produced greater effect than the pure uranium salt. Their logical conclusion w that a more radioactive substance than uranium must be in the ore, a they accordingly set to work to make the separation. After a prodigio amount of labor, which involved long chemical procedures somewhat li those used in qualitative analysis, they found two very active substanc The first, which chemically resembles bismuth, was named *polonium*, honor of Madame Curie's native country, Poland; the second, which chem cally resembles barium, was called *radium*. Since the amount of radi present in the ore was approximately one part in ten million, the di culties were extremely great. As chemical tests for such small quantit of an element were out of the question, the electroscope was used determine which portion of the ore at each step should be retain The final concentrate of radium contained the salt radium bromide, a later the element itself was separated. Pierre and Marie Curie shar in 1903, with Becquerel, the Nobel award for the discovery of radioactivi and the isolation of the salts of the radioactive element; and in 19 Madame Curie was honored by a second Nobel prize.

Other materials were tested for radioactivity, a work which was shar by many investigators and which revealed a number of such elemen

adium, however, due to its great radiative power, which is more than a illion times that of uranium, remains the typical and most representative ement of its class.

/hat is Radioactivity?

The nature of the rays emanating from radioactive substances was of terest to scientists even before the discovery of radium. Rutherford and s associates in England found two types, one which produced intense nization but which was soon absorbed by gases; the other which was more netrating but less of an ionizing agent. The first he called *alpha* (α) ys; the second, *beta* (β) rays. A third type of radiation, much more netrating and resembling X-rays, was found by Villard and was called *mma* (γ) radiation. In addition to ionizing air and other gases, which, we have seen, discharges an electroscope, they affect a photographic ate even through opaque substances, and they excite fluorescence.

By a series of brilliant experiments Rutherford established that the pha rays bear positive charges, that they move with a speed of about n thousand miles per second and are bent from their paths with diffi- lty, requiring strong electric or magnetic fields. By measuring their flection in fields of known strength, he established the ratio of charge mass e/m. By another experiment he measured the charge on each rticle and from these data found the mass to be approximately seventy- ur hundred times that of the electron, or four times that of the hydrogen om. The particle, then, had an atomic weight of four and carried two sitive charges, which indicated that they were helium ions. Rutherford tually collected the particles and found complete proof of their identity h helium. With their relatively large mass and enormous speeds they ve as powerful projectiles, plowing through atoms of gas and disrupt- those with which they happen to collide.

The beta rays were shown by Becquerel to be negative particles. They more easily deflected than the alpha particles but move with a velocity ich varies and may be as high as 160,000 miles per second. They pass

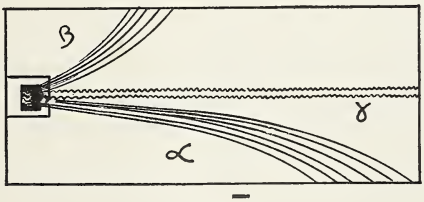


FIGURE 282

pha particles and beta particles are deflected in an electric field; gamma radiation is not.

through several millimeters of metal and may travel through eight or ten feet of air, leaving in their wake a trail of ions. Their negative charge which was established by Pierre Curie, and their e/m value indicate that they are electrons. To acquire the highest speed of beta particles, a cathode ray would have to fall through a potential difference of several million volts.

Unlike the alpha and beta particles, the gamma rays are not affected by the most intense electric and magnetic fields (Figure 282). They are extremely penetrating, passing through a greater thickness of lead than X-rays. They have the characteristics of light and prove to be a radiation somewhat like X-rays but of even shorter wave length.

Significance of Radioactivity

The disintegration of radioactive elements is spontaneous and proceeds at a constant rate not altered by temperature or other conditions. Man has found no way to hasten or retard this decay. We shall see in Chapter 47 how this constant and uniform change serves admirably as a time clock for our estimate of the age of this planet. The "half life" for radium, for example, is sixteen hundred years. One half of any quantity of radium will decompose in that period, and one half of the remaining will decompose during the next sixteen hundred years, and so on. At the end of forty eight hundred years only one eighth of the original specimen will remain. Uranium has a half life of billions of years, and for others it is very brief – a matter of a few minutes.

Radioactivity is distinctive in other respects. Heat in large quantities is evolved. Radium keeps itself above the temperature of the surrounding air and continues to disintegrate, yielding fast-moving particles and rays all carrying enormous quantities of energy, without any drop in temperature. The expulsion of alpha particles, which easily pick up electrons to become neutral atoms, is also an unparalleled phenomenon. Here, it has been observed for the first time that one chemical element is formed from another.

Eighteen of the chemical elements with a total of forty-seven different atomic masses (isotopes) are naturally radioactive. Over eight hundred additional radioactive isotopes have been made in the laboratory by methods which will be discussed in a later chapter. The radioactive elements, both natural and artificial, are being used as "tracers" in chemical and biological research, as a source of concentrated energy, and in medicine.

In the treatment of certain types of cancer, radium and other radioactive substances have been successful. The emanations primarily responsible for the beneficial effects are the gamma rays which destroy diseased tissue more rapidly than normal tissue. Of inestimable value is the stimulus to entirely new lines of investigation of the structure of matter and its related fields which has followed this series of great discoveries. The very

ature of matter is revealed by radioactivity. Particles which emerge om the depths of atoms are fragments of the atoms themselves. The elease of energy which accompanies the expulsion of particles and radiaon from the atom is a consequence of the disruption of the atomic mass hich in the next chapter we shall call the nucleus. That the emanation mes from within the atom is indicated by two facts. First, radium and ther radioactive elements continue to disintegrate whether chemically ee or in their chemical compounds. Second, the beta rays have much ore energy than that required to release electrons from atoms by electric scharge, by heat, or by light.

sitive Rays

The negative particles emitted in streams from the cathode region of scharge-tubes and from various radioactive elements were shown by homson and others to be identical irrespective of the metal in the cathode, e gas in the tube, or the radioactive element. This fact leads to a numr of conclusions. First, electrons are one of the fundamental constituts of all atoms. Second, it follows that all atoms which are electrically utral except when ionized must contain positive particles equal in numr to the electrons. Third, the positive particles must be different either mass or in relationship to the rest of the atom from which the electrons e so easily detached.

The existence of positive particles is shown by the use of a modified thode ray tube. The cathode, placed in the middle of the tube, consists a metal disk with holes. (Figure 283.) Upon discharge, the cathode ys stream toward the anode, but on the other side of the cathode a faint minosity is observed. This effect is due to streams of positive ions which e attracted to the cathode and which, if the field is strong enough, shoot rough the holes and pass on beyond. These positive ions may be dected by a powerful magnetic field and both their mass and charge may determined. The charge, while positive, is always either equal to or is small multiple of the charge on the electron. The masses of these parles vary with the nature of the gas in the tube and sometimes are almost ntical to the masses of its atoms.

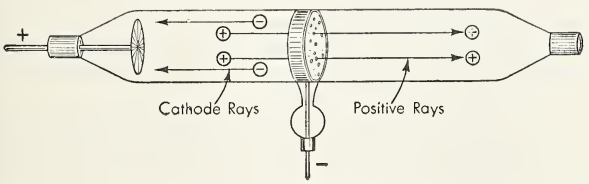


FIGURE 283. POSITIVE RAY TUBE

Positive rays pass through the perforated cathode to space at right.

If the tube contains hydrogen, whose atoms are the lightest and the simplest of all the elements, the positive ray or particle is found to have a charge equal in magnitude to the charge on the electron. Its mass, however, is eighteen hundred and fifty times that of the electron. Rutherford found that this same particle is frequently ejected from many different atoms when their nuclei are struck by alpha particles. He called this positive particle the *proton.*

We may picture the atom, therefore, as an aggregate of electrons, protons, and, as will be shown later, neutral particles which are called *neutrons.* The questions as to the number and arrangement of these particles together with artificial radioactivity and nuclear energy are discussed in the chapters immediately following.

SUMMARY

1. Electrons may be detached from their parent atoms and studied. Such investigations yield knowledge of great scientific and practical value.
2. A charged electroscope may be discharged by flames, radioactive substances, heat, and X-ray, all of which cause the formation of charged molecules, atoms, or groups of atoms which are called ions.
3. The presence of a few ions in the air, under any circumstances, is due to cosmic rays.
4. In the spark discharge of electricity through air some of the air molecules are ionized by collision with ions and electrons which move at great velocities under the influence of the strong electric field.
5. The discharge of electricity through gases at reduced pressures yields cathode rays, which show the following characteristics: (*a*) they are deflected by electric and magnetic fields; (*b*) they cause fluorescence and X-radiation; (*c*) they move in straight lines; (*d*) they exert mechanical and heating effects; that is, they possess a high energy content.
6. Cathode rays prove to be rapidly moving electrons coming from many different elements used as cathodes and are therefore a fundamental constituent of all elements.
7. The discovery of radioactivity was one of the great events of science and followed the discovery of X-rays.
8. Radioactivity includes the spontaneous emission of alpha particles, which are plus-charged helium ions; beta particles, which are electrons moving at great speeds; and gamma radiation, which has a higher frequency and greater penetrating power than X-rays.
9. All electron streams show the same properties; hence we conclude that electrons are fundamental particles of matter, constituents of all atoms, and not symmetrical with the positive particles which are associated with the mass of the atom.
10. Positive rays move toward the cathode in a discharge tube. They consist

the positive fragments of atoms or molecules which have lost electrons. They vary with the kind of gas in the tube.

. The positive ion or ray from hydrogen is the lightest and smallest and is called the proton. This particle, with eighteen hundred and fifty times the mass of the electron, has a positive charge equal in magnitude to that of the electron.

STUDY EXERCISES

. Cite a number of reasons why you consider air to be a nonconductor of electricity.

. What is an ion? Explain the mechanism of ion formation, assuming that there is a source of energy and that the electron is the transferrable particle.

. A charged electroscope carefully insulated and shielded from light gradually loses its charge. Explain in detail the cause, eliminating such possibilities as flame, radioactivity, etc.

. An ion is placed between charged plates in air as shown in the drawing.

(*a*) In what direction does the ion travel?
(*b*) How may its velocity be increased?
(*c*) What impedes its motion?
(*d*) How could it be made to move in the direction opposite to the way it is moving.
(*e*) With the same amount of charge and kinetic energy, which will move faster, an electron or a hydrogen ion?

An electroscope, with either a positive or negative charge, is *quickly* discharged in air by which of these agencies? Check correct answers.

(*a*) Radioactive substances	(*b*) Ordinary light
(*c*) Flames	(*d*) Hot metals
(*e*) A conductor	(*f*) X-ray
(*g*) Cosmic rays	(*h*) Phosphorescent substances

Select by number the *one* correct answer:

(*a*) .... An electroscope with a positive charge is discharged when in contact with ionized air because: (1) it loses positive ions to the air; (2) it receives electrons from the air or from negative ions.

(*b*) .... An electroscope with a negative charge is discharged when in contact with ionized air because: (1) it gains positive ions from the air; (2) it loses electrons to positive ions in the air.

(*c*) .... The rate at which radioactive elements disintegrate: (1) is hastened by the application of heat; (2) is hastened by placing the substance in a strong electric field; (3) is retarded by enclosing the substance in a thick walled lead container; (4) is apparently independent of external conditions and cannot be controlled.

7. Check spaces concerning each of the three types of emanation of radioactiv elements:

	Alpha	Beta	Gamma
Radiation more penetrating than X-rays			
A positive particle			
A negative particle			
Moves with the velocity of light			
Moves with a velocity approaching that of light			
Is not deflected by an electric field			

8. Check each statement in the appropriate blank or blanks if true of cathod rays, positive rays, or both.

	Cathode Rays	Positive Ray
Consist of the residue or molecules which have lost one or more electrons		
Consist of stream of electrons		
Consist of the same particles irrespective of metal in anode or cathode or gas in tube		
Vary with gas or material in tube		
Simplest of them called proton		
Move toward cathode		
Move toward anode		
Are deflected by magnetic or electrical field		
Magnitude of charge is either equal to or a multiple of the fundamental charge on the electron		
Have mass greater than that of the electron		
Mass is $\frac{1}{1850}$ of that of the hydrogen atom		

9. Energy is consumed by a molecule or an atom when, by collision with a fa moving particle, it loses an electron. What may be expected upon the retu of the electron to the ion?
10. Briefly discuss each of the following:
   (*a*) Scientists seek primarily to know and to understand rather than to fi something of immediate use.
   (*b*) Three great discoveries made in the space of a few years — the electr X-ray, and radioactivity — were revolutionary.
   (*c*) The discovery of radioactivity is considered to be one of the great eve of science.

FOR FURTHER READING

1. Eyring, C. F., *A Survey Course in Physics.*
Chapter XVII has a discussion of cathode rays, and radioactivity and a view of atomic structure for the beginner.

2. Lemon, H. B., *From Galileo to the Nuclear Age.*
Chapters 29, 31, 32, and 33 explain the discharge of electricity through gases, cathode rays, the electron, positive rays, and neutrons. The first part of Chapter 34 deals with natural radioactivity. Illustrated by excellent drawings.

3. Robertson, J. K., *Atomic Artillery.*
Chapters IV, V, and VII include discussions of positive rays, radioactivity, and cosmic rays.

4. Millikan, R. H., *Electrons (+ and −), Protons, Photons, Neutrons, Mesotrons, and Cosmic Rays.*
Chapters II and VI provide a more advanced discussion of conduction in gases and the mechanism of ionization of gases.

5. Curie, Eve, *Madame Curie.* Translated by Vincent Sheean; New York: Doubleday, Doran and Company, Inc., 1938.
This is a biography of Marie Curie written by her daughter. The account of her personal life, her struggles against many difficulties in her scientific work, and her great achievements make it an extremely interesting book.

6. Eve, A. S., *Rutherford.* New York: Macmillan, 1939.
The life, letters, and achievements of Lord Rutherford.

25

Atomic Particles

DURING MUCH of recorded history, certain ideas have dominated the thi
ing of man and have motivated him to spend large amounts of time a
energy in their application. One of the most important was that of t
transmutation of the base metals into gold and silver. The alchemi
upheld the notion that all substances were composed of one primitive m
ter — the *prima materia*. To them all substances were essentially simp
and they concerned themselves with the methods whereby they mig
deprive a given form of matter of its characteristic qualities in order
obtain the *prima materia*. It should then be possible, they reasoned,
modification of the *prima materia* to obtain gold. The respectability
this hypothesis of the alchemists can be indicated by its espousal by
eminent Sir Isaac Newton.

The conception of the transmutation of the elements was temporar
terminated by the experiments of Lavoisier. Electrons, X-rays, and rad
activity have proved to be among the most momentous discoveries, howev
for they actually did lead to the discovery of the *prima materia*. These d
coveries represent a great turning point in the history of science. In 18
many physical scientists were sure that practically all the fundamen
discoveries in science had been made. One of the greatest Ameri
scientists of the last part of the nineteenth century, A. A. Michels
stated in 1894, "While it is never safe to affirm that the future of Phys
Science has no marvels in store even more astonishing than those of
past, it seems probable that most of the grand underlying principles h
been firmly established . . . that the future truths of Physical Science
to be looked for in the sixth place of decimals." Within a few years ca
the discovery of X-rays by Roentgen, of radioactivity by Becquerel,
radium by the Curies, and objective proof for the electron by J. J. Thoms
The long sequence of events that culminated in the fission bomb in 1
was thus initiated.

Between the discovery of X-rays in 1895 and the unleashing of nuc
energy over Hiroshima, fifty years elapsed. During those years scien
thinking advanced slowly but surely from one experimental fact to anot

'he solution of the problem of the nature of matter represents the inter-ational aspect of pure science, since workers of many countries — France, taly, England, the United States, Germany, Denmark, Japan, India, and 'anada — participated. From their concerted efforts came our present nderstanding of the atom which now makes the transmutation of one lement into another a commonplace operation. The *prima materia*, so igerly sought for by the alchemist, has been shown to be particles of iatter which represent energy in different forms — electrons, protons, nd neutrons. The solution of the puzzle of the structure of matter is ne of the great achievements of modern science. It has had unexpected ɔcial and economic effects, ranging from cheaper and better electric light ulbs to vastly improved methods of controlling disease.

ıe First Clues

Proof for the actual existence of atoms had to wait until the atomic con-ɔption of electricity had been clearly demonstrated.

In the preceding chapter the evidence for the electrical nature of matter as presented. The simplest positive ion was named the proton by Sir liver Lodge in 1920. By this time the characteristics of the electron ıd proton were well established. They had like quantities of electrical ıarge but possessed opposite signs. The electron is a unit *negative* charge, hile the proton is a unit *positive* charge. In mass, however, they were dically different, since the mass of the proton is equal to the mass of 340 electrons.

Are the electrons and positive particles in an atom in a random state or e they arranged in some regular pattern? In 1911, the first partial but ry significant answer was given in England by Sir Ernest Rutherford. y bombarding gold foil with alpha particles from radium, he was able to ove that the electrons in an atom surround a positive nucleus (Figure 4). Nearly all the alpha particles passed directly through the foil ithout deflection. A few of the particles, however, were scattered, or viated from their path. Since the alpha particles carried a charge of us two, a sudden change in direction could be explained only by their ɔse approach to another concentrated positive charge — the positive ıcleus of the atom. The second conclusion was that the electrons within ı atom must be at relatively great distances from the positive nucleus. ow else could an alpha particle pass through so many atoms without lliding with other positive charges? There could be only one answer: e positive charges must be concentrated in a very small nucleus sur-unded by electrons at a relatively enormous distance from the nucleus. ıis means that an atom must be largely empty space. The atoms are large, as compared with the size of the alpha particle, that a positive ɔha particle goes through about two hundred thousand atoms before it ɔproaches close enough to the nucleus of any one atom to be repelled

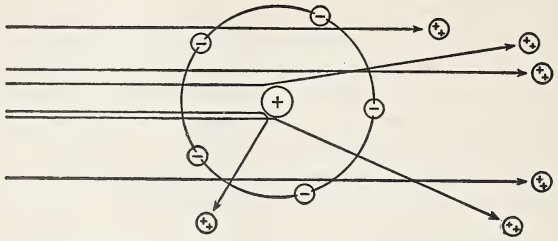


FIGURE 284. PASSAGE OF ALPHA PARTICLES THROUGH GOLD ATOMS

by its positive charge. This early work of Rutherford indicated furth that the magnitude of the positive charge on the nucleus was equal approximately half the atomic weight.

The gold foil experiments were the first to indicate clearly that ato are largely empty space with nuclei of positive charges. In 1914, Mosele a young English physicist who worked in Rutherford's laboratory a who later lost his life in the Dardanelles campaign of 1915 in World War made a second notable advance in studying the atom. He presented t first experimental evidence for the *number* of positive charges (proto in the nucleus. Thus, the nuclear positive charge in the atom of hydrog is one, two in the atom of helium, three in the nucleus of the lithium ato etc. Moseley was able to prove that to each atom could be assigned experimental number which is the number of units of positive char (protons) in the nucleus. This soon became known as the *atomic numb* Since then it has become customary to refer to all elements by number well as by name.

The determination of the atomic numbers of the disintegration produ of radium helped to make clear the nature of the changes in a radioacti process. Radium and other heavy radioactive elements are characteriz by large atomic numbers, large nuclei, and large atomic size. Such la aggregates are so unstable that they disintegrate to form simpler, m stable atoms. The process of disintegration is beyond our control. T actual process of radioactive disintegration always proceeds stepwise, illustrated by the disintegration products of radium:

$$^{226}_{88}\text{Radium}_{1590\text{ y}} \xrightarrow{\alpha} {}^{222}_{86}\text{Radon}_{3.8\text{ d}} \xrightarrow{\alpha} {}^{218}_{84}\text{Radium A}_{3.05\text{ m}} \xrightarrow{\alpha} {}^{214}_{82}\text{Radium B}_{26.8\text{ m}} \rightarrow$$

$$^{214}_{83}\text{Radium C}_{19.5\text{ m?}} \xrightarrow{\beta} {}^{214}_{84}\text{Radium C}'_{10^{-4}\text{ s}} \xrightarrow{\alpha} {}^{210}_{82}\text{Radium D}_{25\text{ y}} \xrightarrow{\beta}$$

$$^{210}_{83}\text{Radium E}_{4.9\text{ d}} \xrightarrow{\beta} {}^{210}_{84}\text{Polonium}_{136\text{ d}} \xrightarrow{\alpha} {}^{206}_{82}\text{Lead}_{\text{stable}}$$

efer to page 458. The periods of half-life are indicated in years (y), ays (d), minutes (m), or seconds (s). The superscript gives the atomic ass, while the subscript gives the atomic number of each element formed the series. Note especially: (1) the loss of an alpha particle *decreases* e atomic number by *two units* and the atomic mass by four units; (2) e loss of a beta particle *increases* the atomic number by *one unit*, by e removal of one negative charge of negligible mass; (3) the alpha parcles eventually form helium; (4) the final products, lead and helium, are ery stable.

A large number of radioactive substances are known, each characterized y a particular path for disintegration which continues until stable end oducts are reached.

etection and Study of Radioactive Elements

The detection of the radiation from radioactive elements, as well as the termination of their periods of half-life, is now easily carried out by a nsitive particle counter, usually referred to as a Geiger counter. This the instrument commonly used whenever it is necessary to detect arged ions in the atmosphere. Thus a sample of lost radium can be und with a Geiger counter. Safety regulations now dictate that works with radioactive substances have a Geiger counter always available to tect the presence of radiation in dangerous amounts.

The Geiger counter reveals the presence of charged particles derived om atoms, either visually by flashing a light bulb or audibly by operating loudspeaker. In Figure 285, *a* represents an ionization chamber with a in window *b*, which may be made of aluminum foil. The central elecde is negative with reference to the outside case. The potential which applied is just slightly less than is needed to cause ionization by cathode ys within the chamber. If an alpha particle or beta particle from an om under study passes through the window into the chamber, ionization

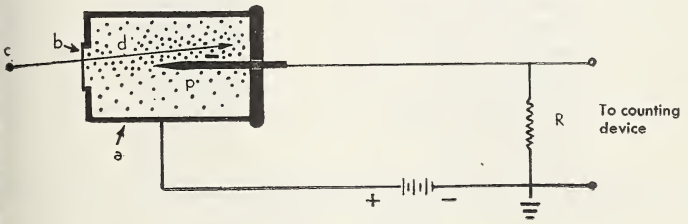


FIGURE 285. THE PRINCIPLE OF THE GEIGER COUNTER
(*a*) *ionizing chamber;* (*b*) *window for rays;* (*c*) *radioactive substance;* (*d*) *ionization by alpha or beta particle;* (*p*) *central electrode.* (*After J. B. Hoag*)

suddenly occurs together with a resultant surge of current. This curren after amplification can be used to "flash" a small light bulb, cause a clickin sound in a loud speaker, or actuate an electric counting device. Th importance of the Geiger counter lies in the fact that it is the most sens tive instrument now available for detecting ionizing particles, whethe they be alpha particles, protons, electrons, or gamma rays. To determin the period of half-life of radioactive sodium, for example, the change i the rate of liberation of charged particles can be followed either visuall or audibly, or actually counted with a Geiger counter, which permits th calculation of the half-life.

Period of Half-Life of Radioactive Elements

Radioactive elements, whether synthetic or radioactive, disintegrate a a constant rate characteristic of each element. The number of disint grations per second, of course, is dependent upon the number of aton present. However, the fraction disintegrating per unit of time is ind pendent of the number taken. For example, consider 1000 atoms of hypothetical element disintegrating at such a rate that 20 per cent disint grate each hour. In one hour, 200 atoms are converted into other ato and 800 of the original atoms remain; at the end of the second hour on fifth of these are gone; that is, 640 remain. The time for all the aton to disintegrate is infinite and this length of time has no real significanc However, the time for *half* of the atoms to be gone is determinable and called the *period of half-life.* Thus in the problem given above, the peri of half-life is nearly 3.5 hours. This means of course, that no matter 100, 1000 or 1,000,000 atoms are involved, half of them will disintegra in 3.5 hours. The periods of half-life of some radioactive elements a given in Table 34.

Table 34. Periods of Half-Life

Element	Half-Life Period
Plutonium — 239	24,000 years
Carbon — 14	4700 years
Radium — 226	1590 years
Sodium — 24	14.8 hours
Polonium — 210	136 days
Phosphorus — 30	2.6 minutes
Chlorine — 33	2.8 seconds

The period of half-life of a radioactive element determined with a Gei counter is one of its most important characteristics.

The work of Moseley had one important consequence. Since an at is electrically neutral, it follows that if it has a nucleus of positive cha there must be a sufficient number of electrons outside the nucleus to ca an equivalent negative charge. Thus, the atomic number of neon is t

iis means that the neon atom has a nucleus carrying ten positive charges d also has ten electrons outside the nucleus. The atomic number can so be defined as the number of electrons outside the nucleus of an atom. iese are often referred to as the planetary electrons. As will be shown er, the chemical properties of an atom are determined by the arrange- nt of the electrons around the nucleus. The nucleus is known to have adius of about 1×10^{-12} centimeters while that of the atom is approxi- itely ten thousand times larger, or 1×10^{-8} centimeters. If by some gical process an atom could be magnified to the size of an orange, the termost electrons would be encircling the nucleus in space at a distance twelve hundred feet. Yes, the atom is almost entirely open space!

The name of Rutherford is associated with much of the unfolding of e story of the atom. In 1919, he accomplished what the alchemists had ed to do: he converted one element into another — nitrogen into oxygen. ie actual quantities involved were exceedingly small but the evidence s convincing and inspiring in its simplicity. Rutherford, at that time, s interested in gathering information about the nucleus of an atom. r example, how stable was it? What would happen if it were hit iarely with a suitable projectile moving at a very high speed? Recall, m page 457, that Rutherford had shown that radium emits alpha par- les as it disintegrates, particles with a mass of four units traveling with peed as high as 10,000 miles per second. The kinetic energy ($\frac{1}{2}mv^2$) of ch a particle is enormous. Rutherford was able to demonstrate that casionally an alpha particle would collide head-on with the nucleus of atom of nitrogen and as a result of the shock of the collision an atom nitrogen would *disappear* but an atom of oxygen and of hydrogen would *pear*. In this process also, the alpha particle disappeared. In scientific orthand, the changes are represented as follows:

$$ {}^{4}_{2}\mathrm{He} + {}^{14}_{7}\mathrm{N} \longrightarrow {}^{17}_{8}\mathrm{O} + {}^{1}_{1}\mathrm{H} $$

e alpha particle was an ion of helium with an atomic mass of four units d a nuclear charge of plus two. Thus a high speed alpha particle when collided with an atom of nitrogen of mass fourteen and nuclear charge seven produced an atom of oxygen of mass seventeen and nuclear charge eight and an atom of hydrogen with one unit of mass and one plus arge. Note that the total nuclear charge before collision $(2 + 7 = 9)$ s the same as after collision $(8 + 1 = 9)$. Similarly, there was conser- ion of mass, since the total mass before collision $(4 + 14 = 18)$ was the ne after collision $(17 + 1 = 18)$.

Ordinary oxygen has long been known to have an atomic mass of sixteen. 1919 it was difficult to account for an atom of oxygen with an atomic ss of seventeen even though it was recognized as an oxygen isotope. entists, however, in 1919 had been prepared for the idea that it was

possible to have atoms of the same element with different atomic weigh
Different forms of the same element with the *same atomic number* b
different atomic masses are called isotopes. Ordinary oxygen is designat
$^{16}_{8}O$. Thus, the oxygen produced in the bombardment experiment
Rutherford was the isotope with mass seventeen, $^{17}_{8}O$. The existence
isotopes had been definitely recognized as early as 1912 in the case of ne
the gas that is responsible for the vivid orange-red color in neon sig
The two forms of neon have atomic masses of 20 and 22.

The masses of atoms are now determined with comparative ease and hi
accuracy with an instrument specifically designed for this purpose, the ma
spectrograph. This instrument can determine atomic masses with a pre
sion of one part in ten thousand. The whole apparatus is in a chamb
which can be evacuated and then filled with a gaseous compound of the at
to be studied. Ionization of this gas is accomplished by a stream of electr
moving under high potential from the cathode C to the anode A. Positi
ions of the atom are produced which, under the repulsion of A and t
attraction of C, are accelerated toward C. (Refer to Figure 286.) Th
positive ions, because of their inertia, pass through the narrow canal i
to form a narrow beam of positive rays. These rays are deflected in
electric field between the plates P_1 and P_2, which are connected to a su
able high electrical potential. H represents the poles of a powerful el
tromagnet. The beam of positive rays, then, behaves like an elect
current surrounded by a magnetic field. Because of the action of
powerful magnetic field between the poles of the electromagnet, the be
of positive rays is again bent and at the same time focused. The amou
of bending of the rays depends upon both the charge and the mass ($q/$
of the ion. As the charge of the ion increases, the bending increases;
the mass of the ion increases, the bending decreases. The net effect
the sorting-out of the positive particles according to mass and charge ($q/$
When they impinge upon the photographic plate P, they produce a l
somewhat analogous to the spectral line produced with a spectrosco
Since the position of the line on the plate is determined by the mass
the positive particles, the instrument itself is referred to as a mass spect
graph. A mechanical analogue of the mass spectrograph is shown
Figure 287.

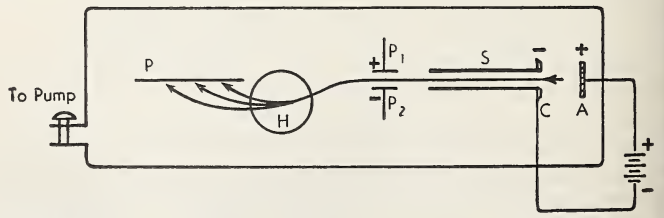


FIGURE 286. THE PRINCIPLE OF THE MASS SPECTROGRAPH OF ASTON

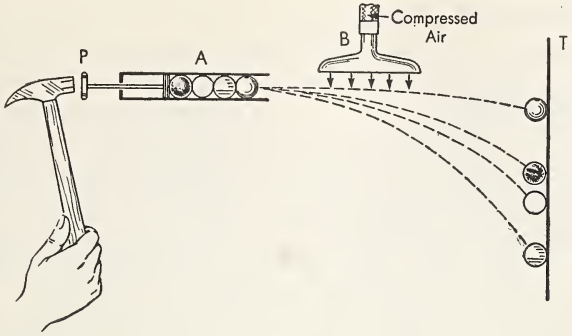


FIGURE 287

balls will be sorted out by the blast of compressed air because they have different masses.

The balls in tube A have different masses. They can be projected rizontally by a blow with the hammer on the piston P. B has a narrow ening through which air is emerging under pressure. As the balls emerge m the tube A, they are subjected to a side push by the rushing air. the balls travel to the target T, they follow a curved path, and the ce where they strike the target will depend upon two factors, the indi- ual masses of the balls and the force exerted by the rushing air. Thus, balls will be sorted in the order of their masses, and the lightest ball l be deflected the most. The apparatus diagrammed in Figure 286 ctions in a similar manner. The positive ions will be deflected from ir original path by repulsion from P_1 and by attraction to P_2. They l be further deviated as they pass through the magnetic field H. The ount of bending of the atoms' path will depend upon the respective sses of the atoms.

When the mass spectrogram of neon was obtained, for example, lines e found corresponding to masses of 20 and 22, which was evidence for two isotopes of neon. These are found mixed in nature in the ratio ninety of neon–20 to ten of neon–22, which accounts for an atomic ght of 20.20. A table of stable isotopes (Table 35) is given on page 476.

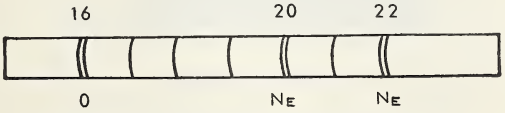


FIGURE 288. MASS SPECTROGRAM OF NEON

Some Methods Used to Study Atoms

The methods used to gather information about the nuclei of atoms a startling in their essential simplicity. Only two of the methods will here briefly described.

1. *The Zinc Sulfide Fluorescent Screen.* In radioactive changes the are produced gamma rays, beta rays, and alpha rays. The alpha ra are doubly positively charged helium particles with a mass of four as co pared with the single charge and mass of the proton, and with a speed high as ten thousand miles per second. This high velocity results in enormous energy. When these particles strike a zinc sulfide screen, t event is signaled by a flash of light. This effect is utilized in the spi thariscope, a scientific toy. When the eye is placed near the lens of t spinthariscope, each collision of an alpha particle with the zinc sulfi screen can be observed as a distinct scintillation. (Refer to Figure 28 In this way a person can watch certain events associated with the d integration of radium. By counting the scintillations, information as the rate of disintegration is obtained; by increasing the distance of t screen, information about the range of the alpha particle and cons quently its velocity and energy can be obtained.

The effect of alpha particles on zinc sulfide is the basis for one of t common applications of radium compounds: the production of lumino dials for watches, clocks, and aviation instruments. The radium co pound is mixed with the fluorescent zinc sulfide. Even though the amou used is very small, the mixture emits visible light. These luminous pai are dangerous; although a watch with a luminous dial may be very co venient, there is a possibility of injury from the radium.

2. *The Fog-Track Machine of C. T. R. Wilson.* This has been the m fruitful device yet perfected for obtaining information about the ato the particles that make up the atom, and the transformation of one ki of atom into another. One great advantage of this device is that cert kinds of events which are the result of atomic changes can be photograph

FIGURE 289. A ZINC SULFIDE SCREEN REVEALS IMPACTS OF ALPHA PARTICLES

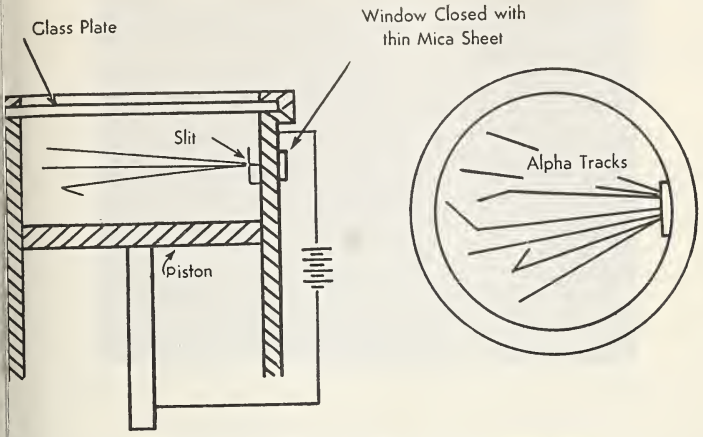


FIGURE 290. ALPHA RAY TRACKS ARE REVEALED BY A WILSON CLOUD CHAMBER

d hence studied at leisure. (Consult Figure 290.) The space above the ston contains enough water to saturate the air with water vapor. By oving the piston up and down, the gas can be alternately compressed d expanded. During compression the air is slightly warmed, but it is ll saturated with water vapor. During the sudden expansion the air xture is slightly cooled and becomes supersaturated with water vapor. a result of this supersaturation there is a tendency for the moisture condense to liquid water again, provided there are nuclei upon which can condense. Alpha particles and beta particles as they travel at high locity through oxygen, for example, knock out planetary electrons from ny of the oxygen atoms, leaving a particle with free positive charges. ie ions left in the path followed by the alpha particle then serve as clei for the condensation of water vapor during the expansion stroke of e piston. Thus, if some radium compound is present at the side of the amber, the emitted alpha particles will ionize the molecules along their th, and water vapor will condense on these ions during the expansion oke of the piston, leaving a fog track which is visible and which can be otographed. (Refer to Figures 290, 291, 292.)

Cloud-track machines are usually constructed so as to be entirely auto- tic, and require no attention during the exposure of as much as a usand feet of motion-picture film. After exposure the individual tures can be thrown on a screen for examination.

Examination of the photograph in Figure 291 shows that most of the cks are straight lines. Occasionally an alpha particle will collide with

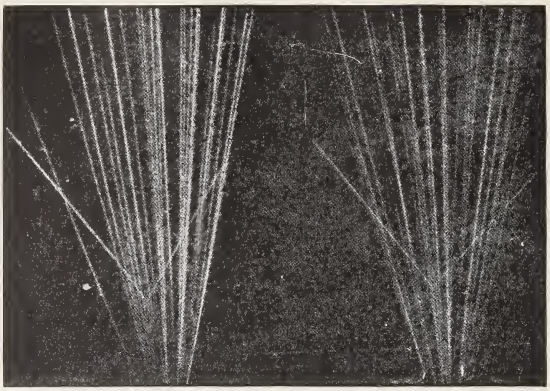


FIGURE 291. CLOUD CHAMBER TRACKS OF ALPHA PARTICLES
Courtesy of P. M. S. Blackett, Cavendish Laboratory

the nucleus of an atom, and the collision will be revealed by a sudde change in direction, or by the formation of two tracks. The latter eve may be evidence of the smashing of an atom, a subject for later treatmer In Figure 292, another cloud photograph, the tracks of many high-spe alpha particles are clearly seen, but note that one alpha particle sudden

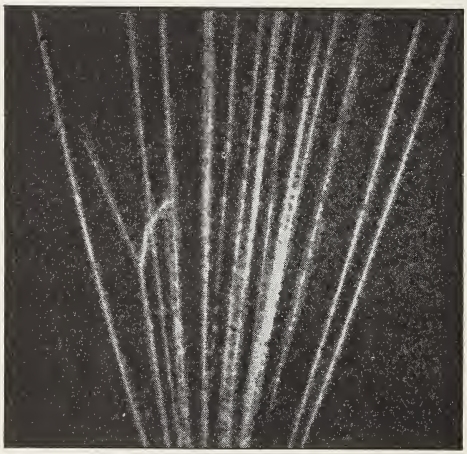


FIGURE 292. CLOUD CHAMBER PHOTOGRAPH OF DISINTEGRATION OF A NITROGEN NUCLEUS $\left({}^{14}_{7}\mathrm{N}\right)$

The cause of the disintegration was the impact with a high velocity alpha particle $({}^{4}_{2}$ *The heavy branch of the forked track was formed by the newly formed oxygen isotope* (*and the fine branch revealed the path of the ejected proton* $({}^{1}_{1}H)$. *(Photograph by P. M. Blackett of the Cavendish Laboratory)*

rmed two tracks. The explanation is that an alpha particle collided th an atom of nitrogen. The very prominent right track is the path of e new oxygen nucleus ($^{17}_{8}O$) and the fine left track the path followed by the ected proton ($^{1}_{1}H$) which was simultaneously produced.

ther Atomic Particles

The transmutation of nitrogen into oxygen, first observed by Ruther-rd in 1919, was one of the notable experiments of the first half of the entieth century. It definitely indicated the possibility of further nthesis of other kinds of atoms by smashing atoms with suitable high ergy particles. One of the most important of these particles was the uteron, the outgrowth of the discovery in 1932, of the heavy isotope hydrogen by Urey, an American. Ordinary hydrogen is $^{1}_{1}H$; heavy drogen or deuterium is $^{2}_{1}H$ and is often referred to as D. Heavy ter is D_2O, with a mass weight per particle (molecular weight) of 20, stead of 18 as in ordinary water. The physical properties of heavy ter are also quite different from those of ordinary water. The freezing int is 3.8° C. for example, as compared with 0.0° C. for ordinary water. Alpha particles from radium easily ionize deuterium by collision,

$$^{2}_{1}H \longrightarrow (^{2}_{1}H^{+}) \text{ (deuteron)} + e$$

form a swiftly moving particle when placed in an electric field. The ization can also be accomplished by the electrons from a hot filament. efer to Figure 293.) The resulting particle is the deuteron.

The positively charged deuterons are set in motion by the electric field. e energy of the deuteron particles can be increased by accelerating em through application of a large potential (three hundred thousand lts) at the ends of the tube. With a suitably designed apparatus and th a sufficiently large accelerating voltage, the energy of the deuterons ting as projectiles can be made very large. The energy of the particle entirely kinetic energy, $K.E. = \frac{1}{2}mv^2$. These high-energy deuterons can

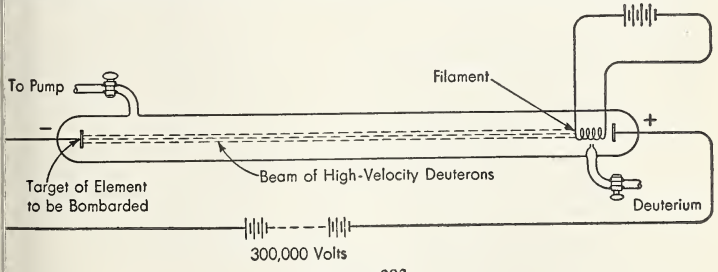


FIGURE 293

Principle of apparatus used to obtain high-energy deuterons for experiments on transformations of elements

Table 35. Stable Isotopes

Listed in Order of Abundance

Atomic Number	Element	Atomic Weight	Mass Numbers	Atomic Number	Element	Atomic Weight	Mass Numbers
1	H	1.0080	1, 2	49	In	114.76	115, 113
2	He	4.003	4, 3	50	Sn	118.70	120, 118, 116
3	Li	6.94	7, 6				119, 117, 124,
4	Be	9.02	9				122, 112, 114,
5	B	10.82	11, 10	51	Sb	121.76	121, 123
6	C	12.01	12, 13	52	Te	127.61	130, 128, 126, 1
7	N	14.008	14, 15				124, 122, 123, 1
8	O	16.000	16, 18, 17	53	I	126.92	127
9	F	19.00	19	54	Xe	131.3	132, 129, 131, 1
10	Ne	20.183	20, 22, 21				136, 130, 128, 1
11	Na	22.997	23				126
12	Mg	24.32	24, 25, 26	55	Cs	132.91	133
13	Al	26.97	27	56	Ba	137.36	138, 137, 136,
14	Si	28.06	28, 29, 30				135, 134, 130,
15	P	30.98	31	57	La	138.92	139
16	S	32.06	32, 34, 33, 36	58	Ce	140.13	140, 142, 136, 1
17	Cl	35.457	35, 37	59	Pr	140.92	141
18	A	39.944	40, 36, 38	60	Nd	144.27	142, 144, 146, 1
19	K	39.096	39, 41, 40				145, 148, 150
20	Ca	40.08	40, 44, 42, 48, 43, 46	62	Sm	150.43	152, 154, 147, 1 148, 150, 144
21	Sc	45.10	45	63	Eu	152.0	153, 151
22	Ti	47.90	48, 46, 47, 49, 50	64	Gd	156.9	156, 158, 155, 1
23	V	50.95	51				160, 154, 152
24	Cr	52.01	52, 53, 50, 54	65	Tb	159.2	159
25	Mn	54.93	55	66	Dy	162.46	164, 162, 163, 1
26	Fe	55.85	56, 54, 57, 58				160, 158
27	Co	58.94	59	67	Ho	164.94	165
28	Ni	58.69	58, 60, 62, 61, 64	68	Er	167.2	166, 168, 167, 1
29	Cu	63.57	63, 65				164, 162
30	Zn	65.38	64, 66, 68, 67, 70	69	Tm	169.4	169
31	Ga	69.72	69, 71	70	Yb	173.04	174, 172, 173, 1
32	Ge	72.60	74, 72, 70, 73, 76				171, 170, 168
33	As	74.91	75	71	Lu	174.99	175
34	Se	78.96	80, 78, 76, 82, 77, 74	72	Hf	178.6	180, 178, 177, 1 176, 174
35	Br	79.916	79, 81	73	Ta	180.88	181
36	Kr	83.7	84, 86, 82, 83, 80, 78	74	W	183.92	184, 186, 182, 1 180
37	Rb	85.48	85, 87	75	Re	186.31	187, 184
38	Sr	87.63	88, 86, 87, 84	76	Os	190.2	192, 190, 189, 1 187, 186, 184
39	Y	88.92	89				
40	Zr	91.22	90, 92, 94, 91, 96	77	Ir	193.1	193, 191
41	Cb	92.91	93	78	Pt	195.23	195, 194, 196, 1 192
42	Mo	95.95	98, 96, 95, 92, 94, 97, 100	79	Au	197.2	197
44	Ru	101.7	102, 101, 104, 100, 99, 96, (98)	80	Hg	200.61	202, 200, 199, 1 198, 204, 196
45	Rh	102.91	103, (101)	81	Tl	204.39	205, 203
46	Pd	106.7	106, 108, 105, 110, 104, 102	82	Pb	207.21	208, 206, 207, 1
				83	Bi	209.00	209
47	Ag	107.88	107, 109	90	Th	232.12	232
48	Cd	112.41	114, 112, 111, 110, 113, 116, 106, 108	92	U	238.07	238, 235, 234

e used to cause transmutations when they collide on the target with the ement to be transformed.

The best known apparatus that has been devised to obtain high-energy uterons is the *cyclotron* devised by American Nobel prize winner, Ernest Lawrence, at the University of California. In effect, the cyclotron is a echanical slingshot for deuterons. vo large hollow D-shaped plates, lled "dees" (*A* and *B* in Figure 294, *a*) e placed between the poles of a powful electromagnet. Provision is made charging these plates positively and gatively by connecting them to a idly oscillating electric current at a potential of 100,000 volts. Gaseous uterium (heavy hydrogen) is ionized at the center *P* by exposure to a hot ament. It is characteristic of ions to travel in circular paths in crossing a gnetic field. Hence the ionized deuterium ($_1^2H^+$) produced at *P* starts veling in a circular path. While the dee *B* is negative and *A* is positive, the uterons are accelerated across the gap G_1 toward *B*. After they have ssed the gap G_1 the polarity of the dees is reversed. Hence the deuons are again accelerated, being repelled by the positive charge on *B* they cross the gap at G_2. Thus each time the deuterons cross the gap twice each revolution — they receive an increment of energy and the ed is increased as a result of proper timing of the oscillating electric rent. The charged particles travel in ever widening circles with ever reasing velocity. When they reach the periphery they are deflected to vindow *W* by a negatively charged plate and emerge as a beam of deuons with velocities of 25,000 miles or more per second to form projectiles h the greatest energy per unit of mass of any produced by man. The clotron will likewise accelerate protons and alpha particles.

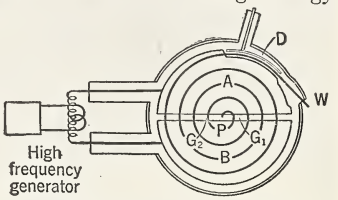


FIGURE 294 (*a*). THE PRINCIPLE OF THE CYCLOTRON
From Lloyd W. Taylor, "Physics," published by Houghton Mifflin Company

The limiting energy of the deuterons in a cyclotron depends upon the mber of times they can be given a "kick" as they cross the gap between dees. This depends in turn upon the radius of the pole pieces of the ctromagnet. The best known of the cyclotrons is the 184-inch instrunt at the University of California (Figure 294, *b*). This dimension ers to the size of the pole pieces. The huge electromagnet weighs over 00 tons and cost $1,500,000. Research with such a cyclotron requires e co-operation of many skilled workers, electronic and electrical engins, physicists, and chemists. The energy of the emergent deuterons in ms of energy per unit of mass is so large that they serve as exceedingly ful packets of energy for the scientist. These high energy particles have de possible the modern methods for transmuting elements.

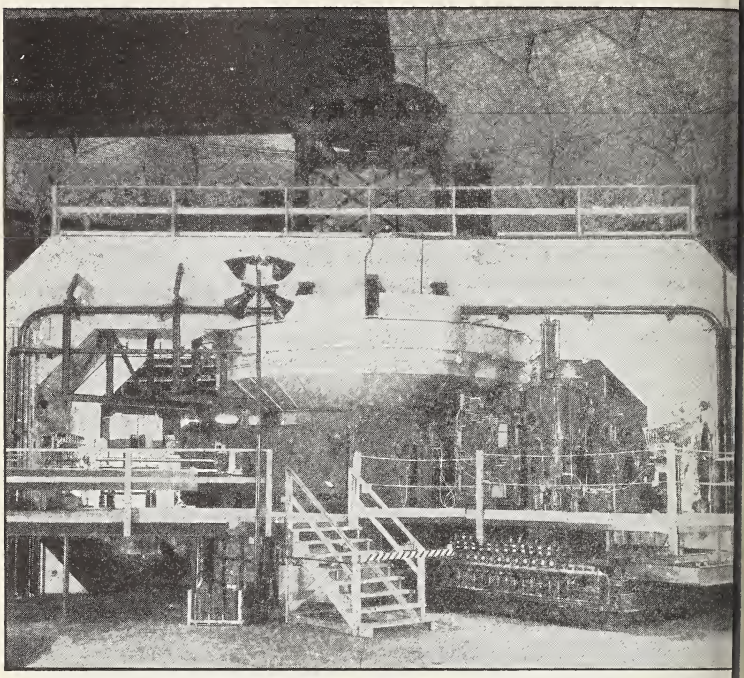


FIGURE 294 (*b*)

A view of the famous cyclotron at the University of California. The pole pieces of huge electromagnet, which weighs over 4000 tons, are 184 inches in diameter. The total c was in excess of $1,500,000. The entire instrument is now surrounded by concrete wa ten feet thick to prevent escape of dangerous radiations. This cyclotron has been a fruit source of many different radioactive isotopes and has been instrumental in unraveling ma of the secrets of the atomic nucleus. (Courtesy of Radiation Laboratory, University of Ca fornia, Berkeley)

Discovery of the Neutron and Positron

The year 1932 was unusual in the number and importance of the d coveries in the field of nuclear physics. Reference has already been ma to the discovery of deuterium by Urey. This year also marked the d covery of the neutron and positron. The existence of the neutron h been predicted by Rutherford and Harkins as early as 1919. Its ident cation was made by an English scientist, Chadwick. The daughter Madame Curie, Irene Curie-Joliot, and her husband, F. Joliot, early 1932 had reported the results of bombarding a beryllium foil with alp particles from polonium. The results were difficult to interpret. Cha

ck showed that they could be explained if the assumption was made at a new kind of particle had appeared which had the mass of a proton t lacked an electrical charge. He proposed, for this neutral particle, e name *neutron*. The existence of neutrons was then demonstrated th a cloud-track machine. Alpha particles from polonium, when they llided with beryllium, ejected neutrons. These were allowed to pass o a cloud chamber. Because of the absence of a charge, the neutron rmed no tracks in the cloud chamber. Nothing was revealed until there s a collision, and then often two tracks were seen because of the shock the collision which resulted in two separate charged particles. (Refer Figure 295.) Thus ordinary nitrogen atoms when struck by neutrons re transmuted into atoms of boron and helium. This change can be mmarized as follows:

$$\text{Nitrogen} + \text{Neutron} \longrightarrow \text{Boron} + \text{Helium}$$

e change can be better represented as follows:

$$^{14}_{7}\text{N} + {}^{1}_{0}\text{n} \longrightarrow {}^{11}_{5}\text{B} + {}^{4}_{2}\text{He}$$

The neutrons were found to have a mass essentially the same as that of e protons but with zero charge. The absence of charge confers unusual operties to the particles. The particles pass through atoms of oxygen d nitrogen in the air without suffering very great retardation. They can netrate with ease dense solids such as lead. They produce few ions in a oud chamber. Neutrons are always set free as the result of some sudden ange in the energy content of the nucleus of an atom. In this process e neutron with zero electrical charge emerges with a large amount of netic energy. It is this kinetic energy which enables it to bump its y through thousands of atoms even in dense forms of matter. The otons and electrons in the atoms can exert no electrical forces of re-rdation. We shall find later that it is this property that makes the utron such a useful and yet dangerous particle. They have however

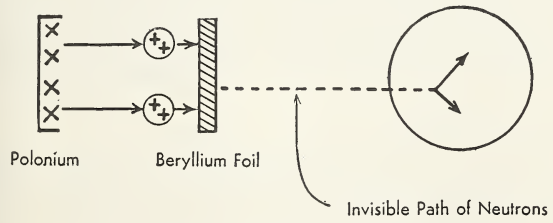


FIGURE 295. DETECTION OF NEUTRONS
(*After J. B. Hoag*)

profound effects on many forms of matter and for this reason researc workers who experiment with neutrons work behind barriers of several fe of water which readily absorb neutrons.

Characteristics of Elementary Particles

For ready reference the essential information concerning the particl that are involved in the structure of the elements is listed in Table 36.

Table 36. Characteristics of Elementary Particles — A Summary

Particle	Symbol	Mass Approx.	Charge	Where Found
Proton	p or ${}_{1}^{1}H$	1	+	(*a*) Hydrogen nucleus (*b*) By collision of hydrogen or of hydrog compounds with alpha particles (*c*) By collision of light elements with alp particles
Electron, or beta particle	${}_{-1}^{0}e$	$\frac{1}{1840}$	−	(*a*) From hot filaments (*b*) From metals by photoelectric effect (*c*) From radioactive substances (*d*) In cathode-ray discharges (*e*) From bombardment of many substanc with X-rays, gamma rays, or alpha ra
Positron	${}_{+1}^{0}e$	$\frac{1}{1840}$	+	Bombardment of lead, aluminum, with c mic rays, intense gamma rays, etc.
Deuteron	D or ${}_{1}^{2}H$	2	+	From heavy water by electrolysis follow by ionization with alpha or gamma rays
Alpha particle	${}_{2}^{4}He$	4	++	From radioactive substances, such as radi
Neutron	${}_{0}^{1}n$	1	0	Bombardment of beryllium, lithium (lig elements) with alpha particles; or heavy w ter ice with deuterons

In using this table, it is necessary to remember that the masses given Column 3 are relative to the weight of the proton and are approxima Actually the masses of the proton and neutron are not unity nor are th exactly the same. Precise measurements show that the mass of the prot is 1.00758 and the mass of the neutron 1.00893 atomic mass units.

The Explanation of Isotopes

The discovery of the neutron as a fundamental particle of matter a energy immediately provided the explanation for isotopes. Thus t nucleus of heavy hydrogen (${}_{1}^{2}H$) consists of one proton and one neutr (pn), while ordinary hydrogen (${}_{1}^{1}H$) has only one proton in the nucleus (The atomic numbers, then, are the same, but the masses are in the ra

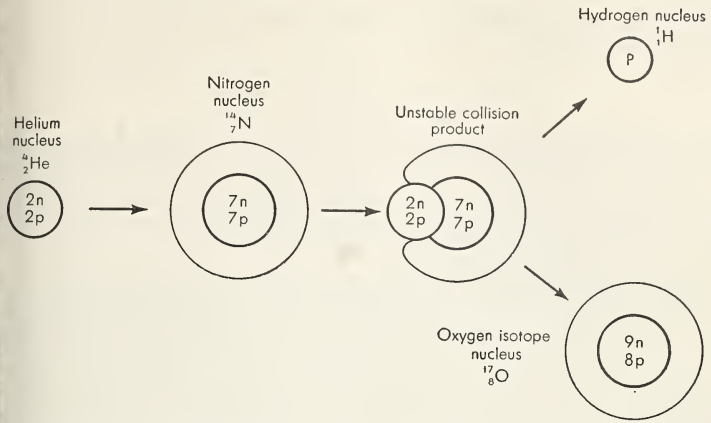


FIGURE 296. TRANSMUTATION OF NITROGEN INTO OXYGEN BY BOMBARDMENT WITH HIGH-VELOCITY ALPHA PARTICLES

two to one. Similarly, the isotope of oxygen discovered by Rutherford O) has a nucleus of eight protons and nine neutrons (8p9n), while linary oxygen ($^{16}_{8}O$) is satisfied with eight protons and eight neutrons 8n). The change that results when a fast-moving alpha particle lides with an atom of ordinary nitrogen is believed to be that indicated Figure 296.

e Equivalence of Matter and Energy

In 1905 Albert Einstein had proposed that matter and energy are differt manifestations of the same thing. According to the relativity theory Einstein, *matter is energy*. The many experiments on radioactivity by e Curies, Rutherford, and others tended to confirm this idea. Thus dium (matter) gives relatively enormous quantities of energy as heat as disintegrates, 3×10^9 calories *per gram*, a process whereby there must be loss in mass. For comparison it can be pointed out that it requires the mbustion of about *one-half ton* of carbon to yield this quantity of heat. Einstein pointed out that

$$E(\text{nergy}) \propto m(\text{ass}), \text{ and}$$
$$E = km.$$

ıe constant of proportionality, k, was the square of the velocity of light. ence,

$$E = mc^2, \text{ or, since } c = 3 \times 10^{10} \text{ cm/sec},$$
$$E \text{ (in ergs)} = m \text{ (in grams)} \times 9 \times 10^{20} \text{ cm}^2/\text{sec}^2$$

According to this equation, the energy associated with *one gram of ma* may seem fantastic,

$$E = 1 \text{ g} \times 9 \times 10^{20} \frac{\text{cm}^2}{\text{sec}^2} = 9 \times 10^{20} \text{ ergs.}$$

This equation indicates the quantity of energy that appears when a gra of matter is annihilated. This energy is equivalent to that obtained b burning over 23,000 *tons* of coal. The equation, $E = m \times 9 \times 10^{20}$ erg has become so commonplace in scientific thinking that it is often referre to as "the Einstein equation."

Many facts pointed to the correctness of the Einstein equation. B 1932, improvements in the machines for producing high-velocity deutero and protons finally permitted an experimental verification of the equatio Cockcroft and Walton in Rutherford's laboratory bombarded a lithiu target with high-velocity protons and photographed the results in a clou chamber. As they had hypothesized, they found that two alpha particl were formed in each collision. The nuclear reaction was shown to be

$$^{7}_{3}\text{Li} + {}^{1}_{1}\text{H} \longrightarrow {}^{4}_{2}\text{He} + {}^{4}_{2}\text{He}$$

The sum of the masses of the particles before and after collision we shown *not* to be the same. On the left (^{7}Li + ^{1}H) they totalled 8.0241; o the right the total mass 2($^{4}_{2}$He) was 8.0056. The *loss in mass* amounted 0.0185 mass units. This amount of mass disappeared as ordinary matt and appeared as the kinetic energy of two high velocity helium ion Other entirely independent work had indicated that the absolute weight an atomic mass unit was 1.67×10^{-24} grams. Hence applying the Einste equation,

$$E(\text{nergy}) \text{ produced} = (0.0185)\ (1.67 \times 10^{-24}\text{g})\ (9 \times 10^{20} \frac{\text{cm}^2}{\text{sec}^2})$$
$$= 2.76 \times 10^{-5} \text{ ergs}$$

per individual collision. This energy of course is distributed over t different helium ions. Since the lengths of the two paths formed by t two atoms of helium were the same, they possessed the same energy. Th also proved that the two particles were identical. From their me ranges, it was possible to calculate the kinetic energies of the two io This turned out to be 2.60×10^{-5} ergs.[1]

Hence, E calculated from loss in mass = 2.80×10^{-5} ergs
E calculated from range of alpha particle = 2.60×10^{-5} ergs.

In view of the many intrinsic difficulties in this research, the check w considered excellent and proved experimentally the equivalence of ma

[1] Calculated from the range of the alpha particles (8 cm), the number of air molecules per u of volume, and the number of collisions before it was stopped.

nd energy as stated by Einstein in 1905. It is one of the most important rinciples of modern science. In a later chapter applications of the law ill be discussed.

SUMMARY

. The modern nuclear theory of the atom had its inception in the experimental work of Rutherford.

. The atomic number of an element is the number of positive charges (protons) in the nucleus of an atom of the element. The experimental method for the determination of atomic numbers was perfected by Moseley.

. Our understanding of the nuclei of atoms was largely made possible by the use of the following experimental procedures: (*a*) the zinc-sulfide fluorescent screen; (*b*) the Wilson fog-track apparatus; (*c*) the Geiger counter; (*d*) the mass spectrograph; and (*e*) the cyclotron.

. Important particles involved in the study of atoms are: (*a*) the proton, (*b*) the electron, (*c*) the alpha particle, (*d*) the deuteron, and (*e*) the neutron.

. Isotopes are different forms of the same element. Their atoms have the same atomic number but different atomic masses.

. Elements consist of atoms of the same atomic number.

. In many nuclear changes matter is converted into energy in accordance with the Einstein equation,

$$E(\text{nergy}) = m \text{ (in grams)} \times 9 \times 10^{20} \text{ cm}^2/\text{sec}^2$$
$$= m \times 9 \times 10^{20} \text{ ergs}$$

. The time necessary for half of the atoms of a given sample of radioactive element to disintegrate is known as its period of half-life.

. The atomic weight of an element is due almost entirely to the number of protons and neutrons in the nucleus.

. The transmutation of one element into another requires a change in the nucleus of its atoms by the utilization of high-energy particles as neutrons, deuterons, or alpha particles. The products are often radioactive elements.

STUDY EXERCISES

. Identify by number the persons responsible for the following achievements:

.. The discovery of the radiation known as X-rays.

.. The American who received the Nobel Prize for the experimental proof of the existence of the positron.

.. The discovery of radioactivity.

.. The American who first provided experimental proof of the existence of heavy hydrogen.

.. The Englishman who, when a comparatively young man, provided a method for the determination of the nuclear charge of an atom.

.. The recipient of two Nobel Prizes for the work which gave us information concerning radium.

.. The man who received worldwide recognition for the determination of the charge and mass of the electron.

1. Moseley
2. Rutherford
3. Millikan
4. J. J. Thomson
5. C. T. R. Wilson
6. Anderson
7. Madame Curie
8. Roentgen
9. Becquerel
10. Chadwick
11. Urey

.... The scientist who was knighted for his early work on the nuclear theory the atom.

.... The man who in 1932 definitely proved the existence of the neutron.

.... An English investigator who had a long, distinguished career in studyi the relations of matter and electricity. He did much of the pioneer wo on the electron and on cathode-ray discharges.

.... Perfected the cloud-track apparatus for studying radioactive changes matter.

2. Name the outstanding developments in the field of nuclear physics and t study of matter that occurred in 1932. Briefly indicate the great significan of each discovery.

3. At the right you will find a list of the particles often mentioned in discussi the modern electron theory of matter. Match by number each parti with the descriptions given:

.... Has unit mass and unit positive charge.

.... Has a mass the same as the electron and unit positive charge.

.... The particle which consists of one electron revolving around a single proton.

.... The particle of unit mass and zero charge.

.... The element which is an isotope of hydrogen and consists of one electron in an orbit about a nucleus of one proton and one neutron.

1. Positron
2. Electron
3. Alpha particl
4. Neutron
5. Hydrogen at
6. Deuterium
7. Proton

.... A particle of mass four and charge of plus two which is emitted by ma elements that undergo radioactive disintegration.

.... A particle with a mass of 1/1850 of that of the proton, with unit negat charge.

.... The atom whose nuclear charge is one plus and whose mass is two.

4. What particle or particles are now believed to account for the mass of atom? For example, how can you account for the atomic weight of carb ${}^{12}_{6}C$, oxygen ${}^{16}_{8}O$, sodium ${}^{23}_{11}Na$, chlorine-35 ${}^{35}_{17}Cl$, and chlorine-37 ${}^{37}_{17}Cl$?

5. What is the distinction between the atomic weight and the atomic numb of an element?

6. What is true of the electrons revolving around the nucleus of an atom a its atomic number?

7. An atom is always electrically neutral even though it contains protons, n trons, and electrons. How can this be accounted for?

8. What is meant by the "period of half-life" of a radioactive element?

FOR FURTHER READING

1. Darrow, Karl K., *The Renaissance of Physics.* New York: The Macmil Company, 1936.

One of America's most effective popularizers of recent developments in physical sciences. The following chapters are recommended for an understa ing of our present conception of atoms: Chapter VI: The Atom Visible; Cha

IX, pages 193–195 and 203–228: Structure of the Atom; Chapter X: Technique of Transmutation (includes an excellent discussion of the cyclotron); and Chapter XI: Victory over the Elements (contains many examples of transmutations).

2. Hecht, Selig, *Explaining the Atom.* New York: The Viking Press, 1947.
   The author presents the story of the atom especially for the layman. Chapters 1 to 4 are especially recommended.
3. Campbell, John W., *The Atomic Story.* New York: Henry Holt and Company, 1947.
   The author combines a thorough knowledge of nuclear physics with a flair for popular writing. Very entertaining. Chapters 1 to 5 especially recommended.
4. Pollard, Ernest, and William L. Davidson, Jr., *Applied Nuclear Physics.* New York: John Wiley and Sons, 1942.
   Readers who are interested in the details of the methods used to study atoms will find this volume very readable. There is a very thorough discussion of the cyclotron in Chapter 4.
5. Curie, Eve, *Madame Curie.* Garden City, N.Y.: Doubleday, 1937.
   The story of a saint of science by her daughter. This is well worth reading.

26

The Architecture of the Atom

THUS FAR in the study of the atom, we have been concerned only with th nucleus. But what about the planetary electrons? The writing of thi story continued apace with the writing of the story of the nucleus; i many ways the unraveling of the mystery of the electrons outside th nucleus has been the more difficult task. Before we arrived at our presen understanding of the extra-nuclear structure of the atom, it was necessar to build up an entirely new conception of the transmission of energ through space, the quantum theory of Planck and Bohr, and a new typ of mathematics, the matrix algebra. This was due to the inherent com plexity of the arrangements of the electrons outside the nucleus. Elemen eleven (sodium), for example, has a nucleus of 11 protons and 12 neutron (11p12n) which is very stable. The eleven electrons which are also a pa of the atom, however, are arranged in space around the nucleus, and th possibilities as to their arrangement are almost limitless, especially sinc it is comparatively easy to change their arrangement.

When Rutherford first proposed the planetary theory of the atom (1911) the external electrons were considered to exist as a diffused cloud sym metrically arranged around the nucleus. But evidence was rapidly accu mulated which indicated that the electrons could not simply exist as a loos swarm. Thus, it was soon shown that they were *not* all alike in thei energy content and that there must be some sort of geometrical arrange ment of the electrons. It was found, for example, that some of the elec trons could be detached in a step-wise and controlled manner. Thi indicated that various electrons in an atom had different but definit energy contents, part kinetic and part potential.

Another independent line of evidence pointing to a definite structure o the electrons in an atom is that the elements can be grouped in familie with similar chemical and physical properties. Thus, neon and argon sodium and potassium, chlorine and bromine, as examples, have man similar properties. If the chemical properties of an element are due t the arrangement of the electrons, then the structure of these pairs o elements must be very definite and should have certain similarities. Ou

resent theory, then, for the arrangement of the planetary electrons in toms has been made possible by studying the energy contents of the lectrons and by correlating this knowledge ith the known chemical and physical pro- erties of elements which have family resem- lances.

As previously shown (refer to page 448), onization of gaseous substances, including lements, can be brought about in a variety f ways, as by (1) light — the photoelectric ffect; (2) heat; (3) X-rays; (4) exposure to adiation as alpha rays; and (5) application f a high potential. For example, an electro- cope is easily discharged by passing a flame hrough the air near the ball-like terminal *A* Figure 297).

The particles (atoms and molecules) which orm air, as a result of being subjected to the igh temperature of the flame, have their inetic energies suddenly increased. An tom of oxygen, for example, contains eight rotons and eight electrons and is electrically eutral. In the violent agitation which esults from the sudden heating, some of he electrons become detached from their toms. The resulting atom then becomes an on with a plus charge — assuming a loss of nly one electron. Some of the free electrons ttach themselves to other neutral oxygen toms to form negative oxygen ions. As a esult, then, of bringing a flame near the harged electroscope, the air in its vicinity contains both positive and egative ions (Figure 297). The positive charge on the electroscope is hen immediately neutralized by some of the negative ions in the air and he leaves collapse. Of course, exactly the same result is obtained if the lectroscope leaves were carrying a negative charge, since the ionized air contains positive ions to neutralize the negative charge on the electroscope.

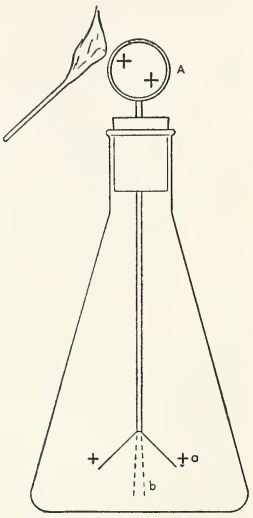


FIGURE 297. IONIZATION OF AIR BY A FLAME

The leaves in position a when the electroscope is positively charged collapse to position b when a flame is brought near A. The same result is obtained if the electroscope is charged negatively.

A similar result is obtained if a sample of radium salt is brought near a harged electroscope. The ions in the air which discharge the electroscope n this case are the result of ionization of the particles in the air by the ast-moving alpha particles from the radium. The electrons in neutral itrogen atoms, for example, are detached from the nuclei to produce aseous ions, which then discharge the electroscope. This process is called onization by collision (Figure 298).

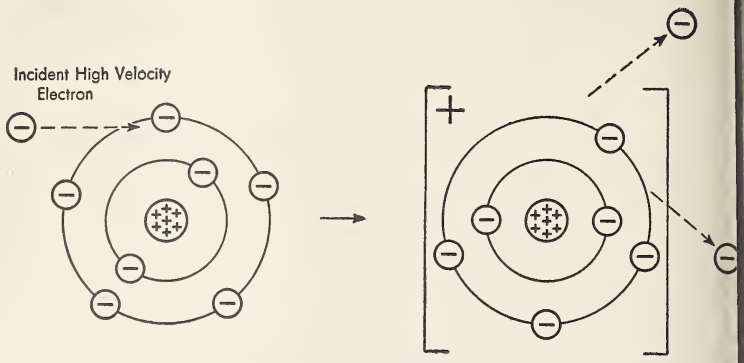


FIGURE 298. IONIZATION BY COLLISION

Schematic diagram to indicate how a neutral nitrogen atom can form a positive ion b the loss of an electron following impact with a high speed electron.

Ionization Energies

Science progresses only as it is possible to make quantitative measure ments and comparisons. The phenomena depicted in Figure 298 ca be followed much more precisely by the determination of the amount o energy actually required to detach electrons and thus produce ionizatio The work involved in ionization is best measured in terms of ionizatio potentials (energies). (Refer to Figure 299.) Electrodes are sealed int each end of the glass tube. To determine the ionization potential of neon, fo example, the tube is first evacuated through opening *a* by means of a suit able pump. A sample of neon is then admitted through *a*. *B* represents bank of electric cells to serve as a source of potential. The battery *C* furn ishes enough current to heat the filament *F* to redness to furnish electron If the contact *D* is so placed that the applied potential is low (1–2 volts) very little current passes through the tube. The contact *D* is slowl

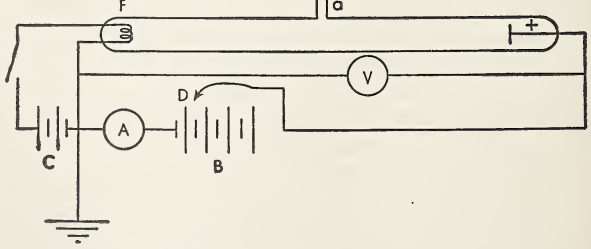


FIGURE 299. DETERMINATION OF IONIZATION POTENTIALS (ENERGIES)

hanged to increase the potential. Suddenly the current flowing through he ammeter A is seen to increase sharply, and simultaneously a red glow s seen throughout the tube. This is the same phenomenon observed in he operation of the common neon sign. The red glow indicates that onization has occurred within the tube, permitting a flow of current. The xplanation is that at the critical ionizing potential the electrons which ave accumulated on the electrode F leave the electrode with sufficient nergy to cause ionization by collision. The process of ionization once tarted continues from atom to atom throughout the length of the tube ntil the entire tube is filled with ions. The potential required to produce onization can then be read on the voltmeter V. This voltage, the ioniza-on potential, then is a direct measure of the energy needed to knock elec-ons out of the atoms of neon, and inferentially this is a measure of the nergy possessed by certain electrons within the neon atom. The ioniza-on potential for neon is 21.5 volts; for helium it is 24.5 volts. This dicates that it is more difficult to ionize helium than neon. Hence, the elium atom is more stable than the neon atom; that is, more energy is quired to detach one of its electrons. A table of the ionization potentials nergies) of some common elements is given in Table 37.

TABLE 37. IONIZATION POTENTIALS (ENERGIES)
(after Pauling)

tomic umber	Planetary Electrons	Element	Electrons Lost (Ionized)						
			1	2	3	4	5	6	7
1	1	H	1.000						
2	2	He	1.80	4.00					
3	3	Li	0.40	5.6	9.00				
4	4	Be	0.70	1.34	11.4	16.0			
5	5	B	0.62	1.79	2.791	19.3	25.0		
6	6	C	0.83	1.79	3.36	4.74	29.2		
7	7	N	1.07	2.18	3.49	5.43	7.19		
8	8	O	1.00	2.58	4.05	5.69	8.07	10.14	
10	10	Ne	1.59	3.02					
11	11	Na	0.38	3.47					
12	12	Mg	0.56	1.11	5.98				
16	16	S	0.76	1.74	2.37	3.48	4.93	6.47	
18	18	A	1.159	2.00					
19	19	K	0.32	2.34					
20	20	Ca	0.45	0.87	3.76				

ote: The figures in this table really represent the energy required to remove electrons from oms in comparison with that necessary to ionize hydrogen. The energy needed to remove the ectron in an atom of hydrogen is 2.16×10^{-11} ergs per electron which requires an ionization otential of 13.54 volts.

A study of Table 37 indicates that the different electrons in atoms do ot possess the same amount of energy. Thus element two, helium, has vo electrons outside the nucleus. The energy required to remove the vo electrons of helium is 5.8 times greater than that required to remove

the electron in an atom of hydrogen. This indicates that the helium atom is a very stable non-reactive atom, in comparison with the hydrogen atom which is confirmed by its known lack of chemical properties. (Refer to page 532.)

Lithium has three electrons outside the nucleus. Note that one of these is very easily removed, but that the two remaining are removed with great difficulty, even more so than those of helium. Note furthermore that one electron in both sodium and potassium is easily removed. In this sense they are similar to lithium. These metals which were discovered in the early part of the last century are called the alkali metals. The order of increasing chemical activity is lithium, sodium, potassium. This is to be expected if chemical activity involves the loss of one electron per atom; that is, potassium with the lowest ionizing potential has the greatest tendency to lose one electron and thus the greatest chemical activity. In contrast, helium, neon, and argon have very high ionizing potentials, which perforce means great atomic stability and low chemical activity. It will be shown later (page 571) that the latter gaseous elements because of their great stability, are part of a family called the inert gases.

It will be further noted that, after lithium loses one electron, the remaining two electrons have energies similar to those of helium. After sodium loses one electron, ten remain about the atom, as in neon. When potassium loses one electron there are still eighteen electrons, just as there are eighteen around the nucleus of the argon atom. Similarly beryllium, magnesium, and calcium each lose two electrons when they ionize or react chemically, leaving two, ten, and eighteen electrons around their respective nuclei, just as in the case of the three alkali metals. All these observations indicate that the electronic structures found in helium, neon, and argon are inherently very stable and are also common to many elements after they have formed ions.

By studying the data pertaining to the energy associated with the various groups of electrons in atoms, chemists began to find explanations for many chemical facts. The outer electron in the potassium atom on the outside of an electronic cloud of eighteen electrons must be much further from the nucleus than the corresponding electron in sodium. Hence by the inverse square law of electrostatics (refer to page 435) the outermost electron is attracted to the nucleus with less force than in the case of sodium. This accounts for its lower ionizing potential and its greater chemical activity. The same line of reasoning accounts beautifully for the greater activity of calcium as compared with magnesium, and of magnesium as compared with beryllium. Here is another interesting comparison. It had been known for a long time that beryllium, magnesium, and calcium have many similar properties. Table 37 reveals that all three lose two electrons very easily. The remaining electrons form configurations around the nuclei similar to those found in helium, neon, and argon.

The first investigator who achieved success in deducing an acceptable hypothesis for the arrangement of the electrons in terms of their energy content was Niels Bohr of Denmark in 1913–14. His work marked "the beginning of a new epoch in the history of the [physical] sciences." As often happens in science, his original hypothesis has been modified, but the basic idea still prevails. This is the Bohr theory of the atom. The theory is highly mathematical and comprehensive in details. Only some of its important aspects can be mentioned here.

The Bohr Theory:

1. The electrons outside the nucleus of atoms have a definite structure which depends in any given atom upon their number (atomic number) and upon their energy — kinetic and potential.

2. The electrons arrange themselves in definite energy levels about the nucleus. There are as many as seven different energy levels in the more complex atoms. These have been designated as the 1 or K, 2 or L, 3 or M, 4 or N, 5 or O, 6 or P, and 7 or Q energy levels.

3. The maximum number of electrons in each level is limited, and these are given by the mathematical series:

$$\begin{matrix} K & L & M & N & O & P \\ 2\,(1^2 & + 2^2 & + 3^2 & + 4^2 & + 3^2 & + 2^2) + \end{matrix} \quad , \text{ or } \begin{matrix} K & L & M & N & O & P \\ 2 & + 8 & + 18 & + 32 & + 18 & + 8 \end{matrix}$$

4. Within each energy level there are various sub-levels, which are designated by the letters s, p, d, and f. These letters refer to the character of the orbits, circular or elliptical, and the energies of the electrons by sub-levels. The two inner sub-levels of each main energy level are designated the s and p electrons. The large and complex atoms also have electrons to two additional sub-levels designated the d and f electrons. It is necessary, however, to avoid the impression that the electrons travel in definite circular or elliptical orbits. If an s electron, in its traveling, for example, could leave a thread of yarn, a fuzzy sphere would soon result, the surface of which locates the region in which the s electron will always be located.

Bohr in his original theory assumed definite orbits for each energy level. This required that the position and velocity of any electron be determinable. But the impossibility of determining the structure of an atom with such completeness finally led to formulation of the Heisenberg uncertainty principle: It is impossible to determine in an atom both the velocity and the position of an electron and useless to try to determine orbits. This of course rules out definite orbits. What concept was substituted? The simpler and statistically more certain concept of an electron cloud. The probability of an electron being in a certain region within a cloud was determinable.

During the thirty years since Bohr first put forth his hypothesis an immense amount of work has been done to determine the energy of the

various electrons and the number of electrons in each energy level in each element. Some of these data will be found in Tables 37 and 38.

Atoms Have Structure

Table 38 reveals the plan for the architectural structure of atoms. Hydrogen has one *s* electron, while helium has two *s* electrons in its one energy level, which is an exceedingly stable one — the *K* level. Lithium has two *s* electrons in the *K* level and one *s* electron in the *L* level. Beryllium and succeeding elements have two *s* electrons in the *L* level. Boron has in addition, a *p* electron in a sub-level, carbon has 2 *p* electrons, nitrogen 3 *p* electrons, oxygen has 4 *p* electrons, and fluorine 5 *p* electrons. This process ends with the 6 *p* electrons of neon, since the electronic configuration of *K* and *L* energy levels of 2 and 2 + 6 electrons is also a configuration of very great stability as in the case of helium. It will be an interesting exercise for the student to show the composition of the *M* energy levels for elements 13 to 17 inclusive. These change progressively by regular additions of one electron to the outside shell and finally end with argon, with 2 electrons in the *K* level, 2 + 6 electrons in the *L* level and 2 + 6 electrons in the *M* level.

Table 38. Arrangement of Planetary Electrons

Element	Atomic Number	*K*	*L*		*M*			*N*	
		1s	2s	2p	3s	3p	3d	4s	4p
H	1	1							
He	2	2							
Li	3	2	1						
Be	4		2						
B	5	Helium	2	1					
C	6	Shell	2	2					
N	7		2	3					
O	8		2	4					
F	9		2	5					
Ne	10		2	6					
Na	11	2	2	6	1				
Mg	12	Neon Shell			2				
A	18				2	6			
K	19	2	2	6	2	6		1	
Ca	20	Argon Shell						2	
Kr	36	2	2	6	2	6	10	2	6
		Krypton Shell							

It is natural to ask if it is possible to draw the picture of the atom. The chemistry texts of only ten years ago usually had neat diagrams of what was purported to be, for example, a picture of a neon atom. Scientists now know that such a diagram is misleading. The uncertainty principle alone eliminates the possibility. What is known, however, is that

en electrons of neon are moving at high velocity in two energy levels, vith two *s* electrons moving in a circular fashion in the first or *K* energy evel, and two *s* electrons moving elliptically and six *p* electrons moving ircularly in the second or *L* energy level. The regions where the elec- rons will be found are often referred to as electron clouds. It is actually impler and better to think only in terms of the various energy levels and ub-levels and the permissible number of electrons in each.[1]

The Structure of the Simpler Elements

The foregoing discussion of the composition of the nuclei and of the rrangement of the planetary electrons of the elements serves as a basis for nderstanding the structure of the simpler elements as given in Table 39.

TABLE 39. THE STRUCTURE OF THE SIMPLER ELEMENTS

Element	Atomic Number — Nuclear Charge	Atomic Mass	Nucleus	Planetary Electrons	Energy Levels *K*	*L*	*M*	*N*	*O*	*P*	*Q*
Neutron	0	1	n	0	0						
Hydrogen	1	1	p	1	1						
Deuterium	1	2	p, n	1	1						
Helium	2	4	2p, 2n	2	2						
Lithium	3	7	3p, 4n	3	2	1					
Beryllium	4	9	4p, 5n	4	2	2					
Boron	5	11	5p, 6n	5	2	3					
Carbon	6	12	6p, 6n	6	2	4					
Nitrogen	7	14	7p, 7n	7	2	5					
Oxygen	8	16	8p, 8n	8	2	6					
Fluorine	9	19	9p, 10n	9	2	7					
Neon	10	20	10p, 10n	10	2	8					
Sodium	11	23	11p, 12n	11	2	8	1				
Chlorine–35	17	35	17p, 18n	17	2	8	7				
Chlorine–37	17	37	17p, 20n	17	2	8	7				
Argon	18	40	18p, 22n	18	2	8	8				
Potassium	19	39	19p, 20n	19	2	8	8	1			

Note: Most elements have isotopes. This table only considers the structure of the most abundant isotope of the above elements.

[1] Thus a brief notation for the structure of zinc $_{30}Zn$ is $1s^2$, $2s^22p^6$, $3s^23p^63d^{10}$, $4s^2$. This very briefly inventories all thirty electrons of zinc in their proper energy levels and sub-levels. Scientific theories and laws are useful for their applications. With the notation for zinc given above, the physicist and chemist can state immediately many of the properties of the metal.

Energy levels	Sub-levels
K 2	2s
L 8	2s
	6p
M 18	2s
	6p
	10d
N 2	2s

The student is urged to study this table and to confirm for himself th following relations:

(1) The number of protons in the nucleus is the same as the atomi number.

(2) The number of electrons is the same as the atomic number.

(3) The mass of the protons and neutrons in the nucleus accounts fo most of the atomic mass. Since the mass of the electron is only 1/184 of the mass of the proton, the effect of the electrons on the mass of th atoms can often be neglected.

(4) The arrangement of the electrons in the various energy levels.

In the study of Table 37, it should be noted that the structures of th family of elements known as the inert gases are characterized by excep tionally stable aggregates of electrons around the nuclei — indicated b their high ionization potentials and a lack of chemical properties. Ele ments with a few more electrons (1–3) than are found in these inert ga structures have properties as metals, due to these "loose" electrons. Thes atoms give up their electrons to become ions with planetary structure similar to those of the inert gases. The relative ease of losing these elec trons is indicated by the low ionizing potentials of the metals. Element with a few less electrons in the outermost shell (1–3) have chemical reac tivity as non-metals, due to a tendency to gain electrons to form ions wit negative charges and with planetary structures similar to those found i the inert gases. A fuller discussion of elements as electron donors an electron acceptors is reserved for a later chapter.

The alchemist sought to find the philosopher's stone by stewing an brewing many strange concoctions with an abiding faith in magic. Th modern alchemist with his knowledge of the particles of energy, proton neutrons, and electrons, has succeeded where his predecessor of the Middl Ages failed. He has relied not merely on hope but on purposeful researc and upon the employment of well-established principles and techniques science. As Newton's principal scientific contribution, the law of univers gravitation, gave an explanation for the mechanics of our planetary systen so the modern electrical theory of matter enables us to understand th planetary-like systems of the sub-microscopic atom. This theory is on of the greatest of scientific achievements. It made the fission bom possible and has made man conscious again of his great responsibility an his great potentiality.

SUMMARY

1. The planetary electrons in atoms possess definite amounts of potential an kinetic energy, resulting from a regular arrangement of electrons in defini energy levels.
2. According to the Bohr theory, atoms consist of planetary systems of ele trons around a positive nucleus. The number of electrons in an atom is th

same as the atomic number and they are arranged in a regular sequence of main and sub-energy levels. When the various levels are complete, the electrons are arranged in the inert gases as follows:

	Energy Level					
	K	*L*	*M*	*N*	*O*	*P*
Helium	2					
Neon	2	8				
Argon	2	8	8			
Krypton	2	8	18	8		
Xenon	2	8	18	18	8	
Radon	2	8	18	32	18	8

3. The chemical reactivity of elements is due to the tendency of their atoms to lose, to gain, or to share electrons and thereby assume stable electronic configurations similar to those found in the inert gases.

STUDY EXERCISES

1. Construct a table similar to that given below for the following elements: Br, Cl, Al, Mg, K, Ca, O, F, He, Be, and Ne.

ement	Symbol	Atomic Number	Composition Nucleus	Electron Arrangement	Tends to lose or gain electrons? Gain	Lose
odium	Na	11	11p, 12n	2–8–1		√

2. What kind of elements are chemically reactive because of a tendency to lose electrons to form a positive ion? What determines the number of electrons to be lost per atom?
3. What kind of elements are chemically reactive because of a tendency to gain electrons to form a negative ion? What determines the number of electrons to be gained per atom?
4. What experimental data can be cited to indicate that potassium is more reactive than sodium, and that calcium is more reactive than magnesium?
5. Compare the atom of magnesium with the magnesium ion, Mg^{++}, as to electronic stability and chemical reactivity.
6. Discuss some of the implications of the "uncertainty principle" in relation to structures of the various electron levels in an atom. What is the meaning of "electron cloud"?

FOR FURTHER READING

1. Briscoe, Herman T., *College Chemistry.* Boston: Houghton Mifflin Company, 1945.

Chapter 3 considers the planetary arrangements of the electrons in atoms and relates the structure to the chemical properties.

2. Babor, Joseph A., *Basic College Chemistry.* New York: Thomas Y. Crowell Company, 1946.

On pages 42 to 48 there is a discussion of the chemical properties of the atoms

as dependent upon the number and arrangement of the electrons in vario energy levels.

3. Richardson, Leon B., and Andrew J. Scarlett. *General College Chemistr* New York: Henry Holt and Company, 1947.

The dependence of the chemical properties of the elements upon t arrangement of the planetary electrons is presented in Chapter 8.

27

Atoms — Old and New

VER SINCE the first so-called atomic bomb was dropped on Hiroshima, in 945, the world has come to talk, think, and write about a new age, the tomic Age. This phrase is really a strange contradiction of ideas, but spite of that fact it has become a part of our language. What is meant, course, is the age of the fission bomb, a bomb in which the explosive aterial utilizes nuclear energy. The Atomic Age actually began on ecember 2, 1942, in Chicago, when it was demonstrated for the first me that a self-sustaining or chain reaction was possible with uranium. he reaction can be likened to an atomic fire always under control in hich the uranium isotope U-235 is consumed, thus releasing energy to nvert the more abundant isotope U-238 into U-239, and eventually to utonium, Pu-239 — one of the principal components of an atomic bomb. he enormous amount of energy needed to initiate this process is supplied the U-235 even though it is present only in the ratio of one atom of -235 to 140 atoms of U-238. The experiment with the uranium pile oved indisputably that the energy that lights the sun and stars had been rnessed by man and was under his control. It was this knowledge and is experience that made the atomic bomb and the Atomic or Nuclear ge possible. The process of releasing the atomic energy of U-235 and utonium is called atomic fission. *The discovery of atomic fission — the nversion of matter into energy by an atomic transformation — is perhaps e outstanding discovery in the history of the human race.* (Refer to page 09.) It is important that we realize the vast potentialities for good and il that lie in our present understanding of the interrelations between atter and energy.

The large-scale utilization of nuclear energy was a conclusion to the quence of events that started with the discoveries of Thomson, Becquerel, d Roentgen in 1895–97 and of the Curies (radium) in 1898. It is an ror to believe that this discovery is something that came suddenly and nexpectedly as a result of the war. In the first edition of the present ook, for example, there occurs the following paragraph:

"As a possible energy source there is one recent development [1939–40]

of great promise. One of the forms of uranium (U-235) has been found t split into barium and krypton atoms with the release of enormous quan tities of energy. One pound of U-235 would liberate energy equivalent t 2,600,000 pounds of coal and would be equivalent as an explosive to fiftee thousand tons of TNT. The problem on which scientists in this countr and abroad are now working [1940–41] is to find a method of separatin U-235 from the other forms of uranium."

The wartime research, then, which led to the atomic bomb, merel carried out, on a scale never dreamed of before, the theories of matt known to chemists and physicists the world over. What had been don in university laboratories on an infinitesimal scale was done on a factor scale. The feverish activity with nuclear energy during the war yea brought no addition to basic knowledge, save the knowledge that uraniu would support a chain reaction which would result in an enormous enhanced conversion of ordinary uranium into fissionable material.

In Chapter 25 it was pointed out that the nuclei of the atoms consi of protons and neutrons. It will be shown, however, that the sum of th masses of all the protons, neutrons, and electrons in an atom is not exact equal to the mass of the atom. The matter which disappears is converte to a very large amount of energy. Consider helium ($_2^4$He), which contai two protons, two neutrons, and two electrons per atom, as a specific exam ple:

2 protons	=	2.01516	atomic mass units
2 electrons	=	0.00110	"
2 neutrons	=	2.01786	"
Sum	=	4.03412	"
Atomic weight of helium	=	4.00390	"
Difference	=	.03022	atomic mass units

Thus, the atomic mass of helium is less than the component parts of th atom by 0.03022 mass units. Applying the equation of Einstein to th formation of 4.00390 grams of helium (6.02×10^{23} atoms), when the loss mass would be 0.03022 grams,

$$E = mc^2 = (0.03022 \text{ g})\ (9 \times 10^{20} \text{ cm}^2/\text{sec}^2)$$
$$= 27 \times 10^{18} \text{ ergs},$$

which is sufficient energy to heat over 7000 *tons* of water from its freezi point to its boiling point. Note that this is the energy released duri the formation of only *four* grams of helium. This example illustrates th true meaning of nuclear *energy*.

Binding Energy of Nucleus

In some way not thoroughly understood, this energy becomes *boun energy* in the nucleus, and contributes to the stability of a nucleus. Th

tability of an atom *increases* as the amount of ordinary energy within he atom *decreases*. Thus, a stone on the slope or top of a hill has more otential energy and is less stable than one at the bottom. The stone oses energy as it rolls down the hill and assumes a more stable position. imilarly, carbon burns in air to form carbon dioxide, liberating energy s heat. The carbon dioxide, then, contains less energy than the original arbon and oxygen and is also more stable. Similarly, the helium atom very stable as a result of a loss of a relatively large amount of energy hen formed. This great stability makes it chemically inert (page 532). he little-understood force needed to form the stable nucleus of an atom often referred to as the *binding energy* of the nucleus. The logic of his term is easily seen when it is pointed out that the energy needed o tear apart the helium nucleus, 27×10^{18} ergs, is the amount liberated its formation. The atoms of the various elements differ enormously in heir stability or binding energy. This is shown in Figure 300. The rdinate represents the "packing factor" for each element, the loss per nit of mass, when an atomic nucleus is formed from protons and eutrons.

The "packing factor" for helium, for example, is (0.03022/4.0330 = 0075 = 00.75 per cent). This means, in essence, that 0.75 per cent of he sum of the original masses of the protons and neutrons in the helium ucleus is converted into energy. Obviously, the greater the packing ctor, the greater is the energy released in its formation and the greater the binding energy and stability of the resulting atom.

A study of Figure 300 indi-tes that the elements with the ost stable nuclei are those with omic numbers between 20 and). Thus, the more unstable uclei are among the very light the very heavy atoms. There the suggestion, too, that the ght elements can be converted to heavier elements with the peration of energy, as well as e suggestion that the very eavy elements can be converted to lighter elements with the peration of energy. Both of ese processes are believed to ke place on a wide scale in the universe. The light-to-heavier changes count for the liberation of energy in the sun and stars. The heavy--lighter transformations are illustrated in radium and all radioactive bstances.

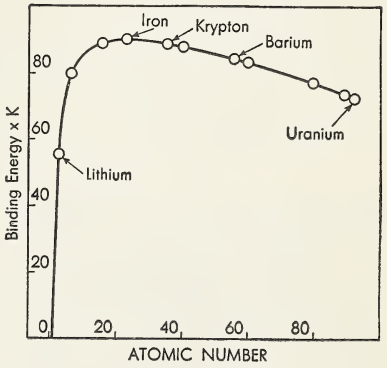


FIGURE 300. BINDING ENERGY OF ATOMS

Source of Energy of Sun

One of the great puzzles that have tried the skill of the greatest scientist in the past is the source of energy of the sun. The energy liberated by the sun each second is staggering in its magnitude. It streams out into space in all directions and only a very small part is intercepted by the earth. Just recall that the diameter of the sun is 108 times the diameter of the earth, and that its surface temperature is over 6000° C. The earth is at least a billion years old (refer to Chapter 48); and during all this time, energy from the sun has been streaming out into space as radiant energy. Moreover, there is nothing to indicate that this rate is sensibly decreasing. Of course, the question about the ultimate fate of the earth and sun is linked to the question of the source of the energy of the sun.

It is easy to demonstrate that the energy of the sun is not the result of the ordinary process of combustion. Strange though it may seem, the sun is much too hot for ordinary combustion. Hypothesis after hypothesis has been invented to account for the sun's energy, but each in turn has had to be discarded because it could not account for all known facts pertaining to the sun. Bethe, an American scientist, proposed (1939) the currently accepted hypothesis to account for the energy of the sun. He postulated the following series of nuclear reactions as occurring in the sun

$$(1)\quad {}^{12}_{6}\mathrm{C} + {}^{1}_{1}\mathrm{H} \longrightarrow {}^{13}_{7}\mathrm{N}$$

$$(2)\quad {}^{13}_{7}\mathrm{N} \longrightarrow {}^{13}_{6}\mathrm{C} + {}^{0}_{+1}\mathrm{e}$$

$$(3)\quad {}^{13}_{6}\mathrm{C} + {}^{1}_{1}\mathrm{H} \longrightarrow {}^{14}_{7}\mathrm{N}$$

$$(4)\quad {}^{14}_{7}\mathrm{N} + {}^{1}_{1}\mathrm{H} \longrightarrow {}^{15}_{8}\mathrm{O}$$

$$(5)\quad {}^{15}_{8}\mathrm{O} \longrightarrow {}^{15}_{7}\mathrm{N} + {}^{0}_{+1}\mathrm{e}$$

$$(6)\quad {}^{15}_{7}\mathrm{N} + {}^{1}_{1}\mathrm{H} \longrightarrow {}^{12}_{6}\mathrm{C} + {}^{4}_{2}\mathrm{He}$$

Reactions (2) and (5) are radioactive changes which liberate positrons (${}^{0}_{+1}\mathrm{e}$). The positron is a particle similar in mass to the electron but with one positive charge. In each of these six reactions there is conservation of mass and energy in accordance with the Einstein equation ($E = mc^2$). Note that the intermediate products, as carbon-13, do not have permanent existence and that the carbon-12 needed to start the reactions is regenerated. The net effect of the six successive reactions is the transformation of hydrogen, plentiful in the sun, into helium. According to this hypothesis the sun is in a steady state in which hydrogen is slowly being converted into helium and energy.

$$4\,{}^{1}_{1}\mathrm{H} \longrightarrow {}^{4}_{2}\mathrm{He} + \text{Energy}$$

The energy liberated is about 2×10^{11} calories per gram of helium produced, which is enough to convert over *four hundred tons* of water to steam.

The hypothesis of Bethe is now generally accepted. Astronomers believe that similar transformations occur in other stars. The hypothesis indicates that the final fate of the sun will depend upon the amount of hydrogen in the sun. When all the hydrogen has been converted into the more stable helium, the sun will commence to cool off and the earth will then be destined for heat death. However, this is not a matter for our immediate concern, for it is estimated that it will take 30 billion years to consume all the hydrogen in the sun.

Artificial Radioactivity

The natural radioactivity of radium, previously discussed, illustrates the production of energy by the conversion of heavy-to-lighter elements. (Refer to Figure 301.) The importance of the discovery of radium may be indicated by the fact that the only person to be awarded the Nobel Prize more than once was Madame Curie, who received it twice — in 1903 and again in 1911 — for her work with radium. In 1935 her daughter Irene Joliot-Curie, jointly with her husband J. F. Joliot, was awarded the Nobel Prize in chemistry. Interestingly enough, the award was made for their discovery of artificial radioactivity, a discovery which has been as productive of new discoveries as was that of radium forty years earlier. It easily ranks as one of the noteworthy experiments of this century.

One of the first instances of artificial radioactivity studied by the team of Joliot-Curie was that observed when aluminum foil was bombarded with alpha particles (Figure 301). A sample of polonium placed at the end of a small round channel in a large block of lead produced a beam of alpha particles. These particles were completely absorbed by a sheet of aluminum foil. (Refer to Figure 301.) However, neutrons were produced in this process. The neutrons were detected by being absorbed in a thick block of paraffin. In this process protons were produced (^1_1H), which were

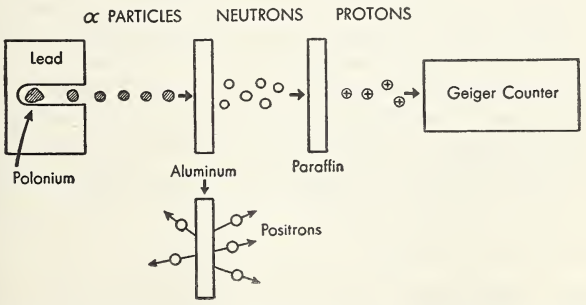


FIGURE 301. CONVERSION OF ALUMINUM TO RADIOACTIVE PHOSPHORUS

easily detected with a Geiger counter. The changes that occurred in the aluminum are more concisely represented as follows:

$$^{27}_{13}\mathrm{Al} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{30}_{15}\mathrm{P} + {}^{1}_{0}\mathrm{n}$$

Thus, the aluminum was converted to an element with atomic number 15 which is an isotope of ordinary phosphorus and found to be radioactive. That is, it in turn emitted charged particles (positrons) which were easily detected with a Geiger counter. Furthermore the rate of emission of charged particles tapered off comparatively rapidly to give a rate curve characteristic of any radioactive substance. There was no doubt that an isotope of phosphorus was produced of atomic weight 30, which was half gone in $2\frac{1}{2}$ minutes. The change which occurred in the radioactive phosphorus was this:

$$^{30}_{15}\mathrm{P} \longrightarrow {}^{30}_{14}\mathrm{Si} + {}^{0}_{+1}\mathrm{e}$$

Hence, positrons were emitted, and the stable substance which remained was an isotope of silicon within the unchanged aluminum foil.

The great significance of this discovery by the team of Joliot-Curie was that for the first time a true radioactive substance was produced artificially in measurable quantities. During the same year they also produced synthetic radioactive carbon-13 and sulfur-29. Their discovery stimulated work in laboratories all over the world and the known examples of artificial radioactivity accumulated rapidly, from three in 1934 to over 370 in 1941 when publication of further discoveries was discontinued because of World War II.

Enrico Fermi, now in this country, was quick to see that neutrons should also be capable of producing synthetic radioactive substances provided the neutron had only sufficient energy to penetrate a nucleus and remain there. Ordinary neutrons were much too fast to be captured when they collided with atomic nuclei. The slowing down of the neutrons was accomplished by surrounding the neutron source with water or paraffin. The frequent collisions of the neutrons with hydrogen atoms as they passed through water or paraffin slowed them up to the point where their kinetic energies were sufficient to just penetrate the nucleus of an atom. The atom was thus converted to an isotope as a result of a gain of one unit in atomic mass. When ordinary salt, which contains $^{23}_{11}\mathrm{Na}$, was treated with slow neutrons, there was produced a radioactive isotope of sodium, as follows:

$$^{23}_{11}\mathrm{Na} + {}^{1}_{0}\mathrm{n} \longrightarrow {}^{24}_{11}\mathrm{Na}$$

The nucleus of this isotope contained 13 neutrons but only 11 protons. This imbalance resulted in radioactivity. The radioactive sodium had a

eriod of half-life of 14.8 hours. The radioactive change was the following:

$$^{24}_{11}\text{Na} \longrightarrow {}^{24}_{12}\text{Mg} + \text{beta rays (electrons)} + \text{gamma rays}$$

he final product is a stable isotope of magnesium.

As a result of vast numbers of experiments carried out since 1934, it is ow known that radioactive isotopes of practically all the elements can e produced. What is needed is an imbalance between protons and neuons within the nucleus. This imbalance can be produced by capture high-energy particles such as neutrons, protons, deuterons, or alpha rticles. The reversion to stability results in artificial radioactivity and ay be the result of the loss of a positron, an electron, or occasionally emission of alpha particles. For example, the radioactivity of sodium- is the result of an emission of electrons and a consequent increase of ie atomic number from 11 to 12, with no appreciable change in mass.

Radioactive sodium can also be produced in relatively large quantities sufficient for experimental purposes in medicine — by bombardment of dinary sodium with deuterons in a cyclotron. The change that occurs the following:

$$^{23}_{11}\text{Na} + {}^{2}_{1}\text{H} \longrightarrow {}^{24}_{11}\text{Na} + {}^{1}_{1}\text{H}$$

hat is one reason why the cyclotron is of such importance and why many illions of dollars are being spent for building and operating cyclotrons.

ie Discovery of Fission

The most spectacular consequence of the knowledge that accumulated rapidly during the nineteen-thirties concerning the atom was the omic bomb. The first clue as to the nature of the unusual radioactive anges that were observed with uranium lay in the statement of Hahn id Strassman in January, 1939, that barium was found in the disinteation products. Barium, atomic number 56, is near the middle of the ability curve shown in Figure 300. The world was ready for the next ggestion for which no one person can claim full credit. The idea of fison came to many nuclear scientists at about the same time, January and ebruary, 1939, in Germany, Denmark, France, and the United States. pparently, the unusual behavior of uranium in the presence of neutrons as a *splitting* of the atom of uranium into two simpler elements of very eat eventual stability, with the simultaneous release of one to three eutrons and an enormous amount of energy. The general process (illusated in Figure 302, *a*) is called atomic *fission*. The term *fission*, adapted om the science of biology, means the disintegration of a parent atom into vo simpler, more stable atoms.

The fission reaction has been intensively studied since 1939. An example fission is the following:

$$^{235}_{92}U \longrightarrow {}^{90}_{36}Kr + {}^{142}_{56}Ba + 3{}^{1}_{0}n + \text{Energy}$$

This indicates that the fission of an atom U-235 produces an atom o krypton, one of barium, three neutrons, and energy corresponding to th loss in mass. The fission reaction is actually very complicated. A many as thirty-four different elements have been found among the fissio products. A more generalized statement for fission is

$$^{235}_{92}U \longrightarrow {}^{85-100}_{36-42}A + {}^{130-150}_{52-62}B + (1-3){}^{1}_{0}n + \text{Energy}$$

Experimentally, it has been found that the elements that predominate i the portion A have atomic masses ranging from 85 to 100 (atomic numbe 36 to 42), while those in the portion B have atomic masses of 130 to 15 (atomic numbers 52 to 62). The atomic masses of A and B are in th ratio of 2:3. The portion A has been found to contain elements such a zirconium, molybdenum, and ruthenium, while the portion B consists o elements such as neodymium, barium, xenon, cerium, and cesium. It very significant that elements of these atomic numbers fall in the centra portion of the curve shown in Figure 300, which indicates that the fissio products are eventually very stable. Thus fission is an example of a tra sition of heavy-to-lighter elements to achieve greater atomic stability.

An invariable product of fission is the formation of one to three neutron which in large enough masses of U-235 or Pu-239 produce more fissio reactions. The whole sequence is referred to as a *chain reaction.* Th chain reaction once started proceeds with explosive violence.

A third very significant aspect of atomic fission is the conversion of som matter into energy. It is estimated that about 0.1 gram in each 10 grams of U-235 is converted into energy. This energy is truly enormou Consider an atomic bomb containing only one kilogram (2.2 pounds) o U-235. The energy released at fission, according to the Einstein equatio is

$$E(\text{nergy}) = (0.10\text{g}) \left(\frac{1000}{100}\right) (9 \times 10^{20}\ \text{cm}^2/\text{sec}^2)$$
$$= 9 \times 10^{20}\ \text{ergs}$$

One of the heaviest handiworks of man is a modern battleship with mass of 45,000 tons. The energy represented by 9×10^{20} ergs is sufficie to lift such a battleship a hundred *miles* above the earth's surface. Tha is the result of the release of *nuclear energy*!

The fission of uranium is always accompanied by the release of gamm rays in amounts never realized before. Further, the fission products a themselves usually radioactive and continue to give off dangerous amoun of gamma rays and other radiations over a long period of time until stab forms of the elements result.

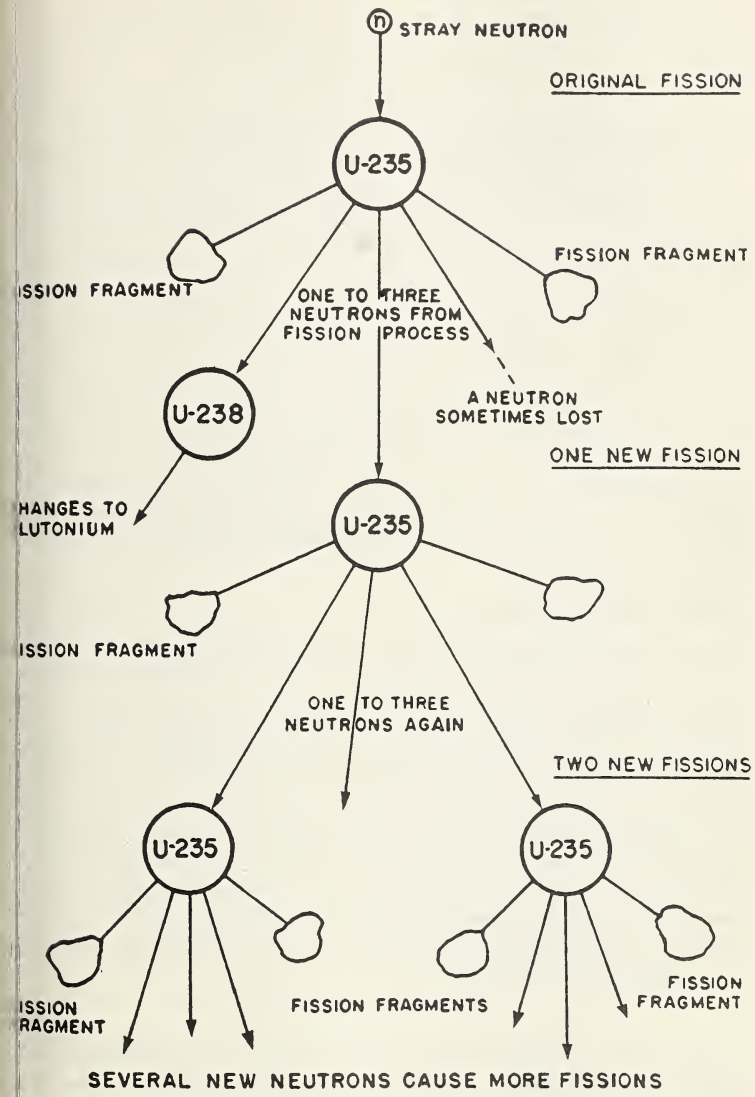


FIGURE 302 (*a*). A CHAIN REACTION IN U-235
(*From H. D. Smyth, "Atomic Energy for Military Purposes," Princeton University Press*)

It was easy to foresee, in 1939, that atomic energy released in a chai reaction could be used in the production of bombs (Figure 302, *a*). stray neutron serves as a trigger to start the chain reaction. This produce fission in one atom of U-235 and simultaneously produces one to thre neutrons available for producing fission in other U-235 atoms. Th resulting chain reaction then proceeds with unprecedented violence.

It was quite clear in 1940 that atomic fission had three major implica tions: the sudden release of energy in stupendous quantities; the productio of fission fragments which were themselves radioactive but which eventu ally assumed very stable forms; and the possibility of a neutron chai reaction using uranium-235. It was further known that we possessed n monopoly on atomic fission, so there was the appalling possibility that ou enemies might be working on the bomb. Secretly the production of atomi bombs became a significant part of our national defense. The tim between 1940 and 1945 was occupied with feverish, intensive researc which was guided by the keenest minds in nuclear physics and whic involved the construction of huge factories, the labors of over 60,00 individuals, and the expenditure of over $2,000,000,000. All this effo was to culminate in the atomic bomb, which quickly destroyed the wi to resist on the part of the Japanese people, and thus shortened Worl War II by many months and saved hundreds of thousands of America lives in the armed forces.[1]

Synthetic Fissionable Material

Of the many problems involved in the production of atomic bombs, a least two were crucial: namely, the production of fissionable materials i quantities large enough to make bombs, and the determination of th critical size of the bomb in order to bring about atomic fission. It wa early demonstrated that atomic fission occurred with just one of the natur isotopes of uranium, U-235. This occurs only to the extent of 0.70 pe cent in ordinary uranium. To make an atomic bomb of U-235 woul require the separation of that isotope from the relatively abundant an stable U-238. However, it was early realized (1940) that there was th possibility of converting the stable isotope U-238 into fissionable materia Fermi and others had shown that U-238, by neutron capture, could b converted into two new synthetic elements of atomic numbers 93 and 9 The reactions were as follows:

$$^{238}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \longrightarrow {}^{239}_{92}\mathrm{U}$$

This isotope was short-lived, having a half-life of 23 minutes; and b emission of an electron it formed a new element which was named nep tunium.

$$^{239}_{92}\mathrm{U} \longrightarrow {}^{239}_{93}\mathrm{Np} + {}^{0}_{-1}\mathrm{e}$$

[1] Cf. K. T. Compton in *The Atlantic Monthly*, 178, No. 6 (December, 1946), pp. 54–56.

This likewise was short-lived, with a half-life of 2.3 days, but it formed the relatively stable plutonium-239 with a half-life of 24,000 years.

$$^{239}_{93}\mathrm{Np} \longrightarrow {}^{239}_{94}\mathrm{Pu} + {}^{0}_{-1}\mathrm{e}$$

Plutonium-239 is the isotope which has played such an important part in making possible the atomic bomb. Like U-235, it undergoes atomic fission. Note that this series of reactions (given above) changes U-238, which is useless in an atomic bomb, into plutonium-239, which is fissionable. The neutrons for producing this change originate in the very small amount of U-235 (0.70 per cent) present in ordinary uranium. On December 2, 1942, what heretofore had been largely theory became an accepted fact, for the first self-sustaining nuclear chain reaction or uranium pile went into operation on that date and operated continuously for a period of weeks. It was called a uranium pile because it was, literally, a pile of uranium rods interspersed with graphite rods. The latter served to slow up the neutrons from the fission of U-235 to speeds which would permit capture by the many atoms of U-238 and thus the formation of Pu-239. Because of this function the graphite is termed a moderator. The energy of the neutrons thus de-energized appears as heat within the pile. In this feature of the operation of a uranium pile lies the possibility of power from uranium.

The atomic bomb project consisted, then, of a number of essential steps, such as the conversion of U-238 to Pu-239 in a uranium pile, followed by the separation of the plutonium. Even under the stress of war conditions, the recovery of the plutonium was as high as ninety per cent. It is natural to question the safety of U-235 or Pu-239 in quantity and to wonder how the explosion can be prevented until needed. Fission cannot occur in a chain reaction unless the mass of fissionable material exceeds a critical amount. Neutrons from the fission from U-235 can escape from the uranium to the surroundings. This will happen if the mass is too small. Beyond a certain critical size, however, the neutrons will remain within the material, so that the production of neutrons by fission exceeds the rate of absorption or loss of neutrons. Then disintegrative fission occurs suddenly. In the fission bomb this is brought about by having at least two masses of U-235 and/or Pu-239, each somewhat less than the critical size, which can be slammed together at the desired moment by a suitable bomb mechanism to produce an explosion. This reaction accounts for the fact that an atomic bomb may contain both U-235 and Pu-239.

Fission Bombs

To date (1950) seven atomic bombs have been detonated, the first test bomb at Alamogorda, New Mexico, on July 16, 1945; the bombs which destroyed Hiroshima and Nagasaki, on August 6 and 9, 1945; and the two experimental bombs used at Bikini Atoll in the Pacific in July, 1946.

FIGURE 302 (*b*). EXPLOSION OF ATOM BOMB NO. 5 IN BIKINI ATOLL LAGOO

The column and cloud over the site of the explosion is composed mostly of water and stea heavily contaminated with a great variety of radioactive products dangerous to life. T diameter and height of the column and cloud can be estimated by a comparison with t lengths of the vessels anchored in the lagoon. The size of the column is an indication of t enormous amount of energy released at the time of the explosion. (*U.S. Air Forces Phot graph*)

ll persons who have witnessed these explosions attest to their awfulness. ince 1946 two additional bombs have been detonated.

The damage was caused by three massive effects, the first of which was great shower of intensely penetrating radiation — neutrons, gamma rays, lpha and beta rays. These rays at Hiroshima were lethal over an area of square mile beneath the point of explosion and caused bodily injury up o a distance of 7500 feet. The second massive effect was that of heat. eople were burned at distances as great as two and a half miles and fires ere started in buildings as a result of the radiant heat of the Hiroshima omb at distances of two miles. The third massive effect was that due o the blast or pressure wave as a result of the air at the place of explosion eing suddenly heated to temperatures of millions of degrees. At Nagaki, brick structures at a distance of 6000 feet were destroyed. In the ase of Hiroshima all three of the effects just mentioned — radiation, heat, nd blast — resulted in about 75,000 deaths, with an equal number injured, nd in the complete destruction of the city which had a normal population over 340,000.

It is now recognized that the pressures of World War II merely accelated the steps toward nuclear power. The bombs based upon atomic ssion hastened the conclusion of the war, but at the same time brought l civilizations face to face with their most urgent problem — what to o about the institution of war. Can it be abolished or must it continue? his is the most important question facing mankind today. The answer as not been found, but the problem largely shapes the collective thinking the peoples of all nations, their politicians and their statesmen. Scientsts can only point out and re-emphasize that there are certain accepted cts in regard to nuclear energy:

1. Fission bombs can now be made relatively cheaply and in great number. hey will become more destructive.
2. At present there is no practical defense against atomic bombs, and none n be expected.
3. Other nations are working on the production of fissionable materials nd will produce bombs.
4. Preparedness against atomic war is futile and, if attempted, will probably in the structure of our social order.
5. If war breaks out, fission bombs will very probably be used.
6. There is no solution to this problem except international control of atomic ergy and, ultimately, the elimination of war.[1]

uclear Energy in the Service of Man

While politicians and statesmen argue and declaim on control of atomic ergy, scientists quietly continue their research. In fact, more than 800 tificial radioactive elements are now known. Radioactive forms of all e known elements have actually been produced. The work with the utonium development has resulted in vastly superior methods for the

[1] Emergency Committee of Atomic Scientists, Inc., Albert Einstein, Chairman.

production of these isotopes, so that many of the most useful ones are no being produced in relatively large quantities and at comparatively lo cost. Experimentation with these materials has been enormously acce erated. Many persons believe that the greatest benefits to humanit from our growing knowledge of atomic energy will come from the solutio of baffling problems in medicine, biology, industry, agriculture, metallurg physics, chemistry, entomology, and many other fields, by the widespre use of radioactive isotopes rather than from potentially abundant powe Consider, as examples, the use of synthetic radioactive substances in med cine. Radium, of course, was the first radioactive substance used fo curative purposes, but it has some serious limitations, not the least o which is its relatively great cost. Furthermore it is difficult or impossibl to use in the case of deep-seated infections and the dosage is difficult t regulate. Radioactive sodium (refer to page 502) is free of these limi tations. It disintegrates as follows:

$$^{24}_{11}\mathrm{Na} \longrightarrow {}^{24}_{12}\mathrm{Mg} + {}^{0}_{-1}\mathrm{e} + \text{gamma rays}$$

It can be produced for a small fraction of the cost of radium. Its perio of half-life is comparatively short — 14.8 hours — as compared wit nearly sixteen hundred years for radium. The salt with radioactiv sodium can be administered internally with proper dosage for medicina ends within the body, and after it has emitted the curative gamma rays i forms a harmless substance — a magnesium salt. The beneficial effects o radium and other radioactive substances in the treatment of disease ar due to the effect of gamma rays on disease organisms or infected tissu A recent report (1947) indicates that radioactive sodium has provided, fo the first time, a rational treatment to eliminate the edema in congestiv heart failure.

Medical science has already seen the possibilities of using artificiall produced, "tailor-made" radioactive substances which are cheaper an more effective than radium in the treatment of disease. Deep-seate bone infections, for example, which are very difficult to cure, migh respond to treatment by some form of radioactive phosphorus, produce with deuterons by the reaction

$$^{31}_{15}\mathrm{P} + {}^{2}_{1}\mathrm{H} \longrightarrow {}^{32}_{15}\mathrm{P} + {}^{1}_{1}\mathrm{H}$$

Experimentation has shown conclusively that radiophosphorus is quickl deposited, largely in the skeletal structure and especially in the bon marrow, the seat of origin for white blood corpuscles. In leukemia, state wherein the white blood corpuscles multiply too rapidly, a patie has shown improvement when given doses of radiophosphorus. (Ref to Figure 303.) Another approach to diseases within the bones is by th

FIGURE 303. RADIOACTIVE PHOSPHORUS IN A RAT

n four and a half hours after injection, the radioactive phosphorus had gone to nearly parts of the rat's anatomy including vertebrae in its tail. Photograph was made by laying rat on top of a photographic plate. (By LIFE photographer Fritz Goro. Copyright ME Inc.)

use of radioactive strontium produced with neutrons from the mo abundant isotope of strontium.

$$^{88}_{38}\mathrm{Sr} + {}^{1}_{0}\mathrm{n} \longrightarrow {}^{89}_{38}\mathrm{Sr}$$

Thus, infection of the bone marrow — osteomyelitis — is deep seated, ar treatment with radium on the surface of the body is ineffective. As bo tissue is largely calcium phosphate, an ideal treatment would be the admi istration of radioactive calcium. Unfortunately, a suitable radioacti form of calcium is not readily available. But strontium phosphat because of the known similarity of strontium to calcium, should be able function in bone tissue as calcium phosphate. Experiments have sho that when a soluble form of strontium-89 is administered internally, it very quickly deposited uniformly throughout the bony structure. It th disintegrates slowly — it has a half-life of 55 days — to give off its radi active curative rays within the diseased area.

The radioactive isotopes have in fact led to a new type of chemistr Chemists can now actually tag molecules and follow them through complex series of changes in either plant or animal life. The work wi tracer atoms has been so fruitful that some biologists and medical m say that artificial radioactivity is "probably the most useful tool f research since the discovery of the microscope." Hitherto unanswerab questions pertaining to the human body are now easily answered. Su a problem is the determination of the volume of blood in the human bod A known amount of a solution of radiosodium ($^{24}_{11}\mathrm{NaCl}$) can be injected in the blood stream. After a short wait for thorough mixing, a small samp of blood is removed for analysis with a Geiger counter. From the chan in the Geiger count, the total dilution of the volume of blood is easi calculated. Another example of tracer technique is the use of radioacti iodine, artificially produced, in studying diseases of the thyroid glan This gland, through its synthesis of the iodine-containing hormone, th roxine, determines the character of the metabolic processes. Mere trac of radioactive iodine-128 can be given to a patient and the rate of absor tion by the thyroid determined with a small portable Geiger counter he to the throat. Signals from the iodine absorbed by the thyroid appe within a very few minutes after ingestion. Iodine-128 has been wide used in treatment of cancer of the thyroid gland, in many cases eradicati the cancer and preventing its recurrence.

One of the most useful radioactive tracer elements is carbon-14. Th is easily synthesized by the reaction between ordinary nitrogen and sl neutrons.

$$^{14}_{7}\mathrm{N} + {}^{1}_{0}\mathrm{n} \longrightarrow {}^{14}_{6}\mathrm{C} + {}^{1}_{1}\mathrm{H}$$

his isotope is two units heavier than the common form of carbon (C-12). hemically, however, it is very similar. It disintegrates with the libera- on of electrons with a half-life of 4700 years to form ordinary nitrogen.

$$^{14}_{6}C \longrightarrow {}^{14}_{7}N + {}^{0}_{-1}e$$

growing plant, for example, can be placed in an atmosphere which ntains radiocarbon dioxide. The absorption of the carbon dioxide in ıe growing leaf is easily demonstrated with a Geiger counter, or by laying leaf on photographic film. The film, when developed, reveals the shape the leaf. The disintegrating C-14 in this case affects a photographic m just as does radium. Petroleum or coal formed many millions of ears ago contains no radioactive carbon. An Egyptian mummy, however, ill still have large amounts of radioactive carbon, and thus it is possible date the burial within historic time, since the half-life of this form of rbon is 4700 years. The new science of radiochemistry or tracer chem- try promises much in advancing our knowledge of many different aspects plant and animal life. Geiger counters and carbon-14 have already come common tools for research by biologists, medical men, and chemists. The use of the cyclotron and other techniques of nuclear study to push ıck the curtain before the great unknown is admirably illustrated in the scovery of elements 43, 61, 85, 87, and the trans-uranium elements, 93 98. Previous to 1935, the known elements had numbers as high as 2. But the series was not continuous since there were many gaps, such s for numbers 43, 61, 85, 87. The existence of these elements could be ıspected but definite proof for their existence had to wait their actual nthesis by the use of high-energy deuterons or alpha particles in a clotron or by the use of neutrons, which can also be obtained indirectly high concentrations in a cyclotron.

Element 43 was obtained by bombarding molybdenum with deuterons neutrons in 1937. Because it was the first element artificially produced, has been named technetium or Tc. It has since been found in the fission roducts of uranium. An isotope of element 61 has been prepared and has een named promethium. In 1940, in bombarding bismuth with high- nergy alpha particles, element 85 was synthesized. This element is similar chemical properties to chlorine, bromine, and iodine, but has a half-life only 75 hours. This accounts for its absence in the earth's crust and kewise its name, astatine, meaning unstable. Its symbol is At. A rench woman scientist, Marguerite Perey, discovered element 87 in 1939 the disintegration products of actinium, when it lost an alpha particle. his was found to be a metal, exceedingly active and similar to cesium, ıbidium, and potassium. Since this element has a half-life of only 21 inutes, it cannot be found on the earth. The discoverer named the ement francium (Fr) for her native country.

The story of elements 93 and 94, neptunium and plutonium, has alread been told in this chapter. Other trans-uranium elements, 95 and 9 were also discovered during the early nineteen-forties and were all mad artificially. One of the group, plutonium, has since been found in natur being found with uranium in mere traces, one part in 10^{14} parts. Elemer 95 was discovered after bombarding U-238 with alpha particles in a cycl tron. It was found to have chemical properties and a structure simila to the element europium. Hence it has been named americium, or Am after the Americas. It is a comparatively short-lived element. Plutonium 239, when bombarded in a cyclotron with alpha particles, produced elemer 96, which was named curium after the Curies. Its symbol is Cm. Th element has a number of isotopes with half-lives as short as one montl Hence it is easy to see why it is not found in nature. The newest syntheti elements are berkelium (symbol Bk, atomic number 97) and californiur (symbol Cf, atomic number 98), produced in 1949 and 1950 with the gian cyclotron at the University of California.

Atoms — old and new! There is now definite proof for the existenc of ninety-six different elements all consisting of various numbers and co figurations of protons, neutrons, and electrons. Practically all these el ments exist in isotopic forms and there is no doubt that many new isotop forms remain to be discovered. The command of the alchemist ov nature was indeed insignificant when compared with that of the presen day physical scientist.

SUMMARY

1. The atomic weight of an atom is not precisely the sum of the masses of th protons, neutrons, and electrons in the atom. The difference in ma represents matter converted into energy.
2. The mass loss involved in the formation of an atom becomes its bindi energy. This amounts to 9×10^{20} ergs (2×10^{13} calories) per gram loss mass. This amount of energy is equivalent to the heat obtained in burnir 3×10^{10} tons of a high grade coal.
3. The most stable elements are those of intermediate atomic number. El ments of low atomic number have a tendency to become more stable b undergoing changes which result in an increase in atomic number. Elemen of high atomic numbers have a tendency to become more stable by disint grating to form elements of lower atomic number.
4. An important example of a light-to-heavier transformation of an element the conversion of hydrogen into helium in the presence of carbon as it believed to occur in the sun.
5. The transformation of heavy-to-lighter elements is the cause of natur radioactivity. In radioactive charges, disintegration may form two or mo of the following kinds of particles: alpha particles, beta particles, positron and neutrons, as well as gamma rays.
6. The transformation of an element into a radioactive form by bombardmer

with high energy particles (deuterons, protons, alpha particles, or neutrons) results in synthetic radioactive elements or artificial radioactivity.

7. Radioactive forms of practically all elements can be produced. Many of these are now utilized as tracer elements in the new science of tracer chemistry or radiochemistry.

8. Certain elements of high atomic number and odd atomic mass, notably uranium-235 and plutonium-239, undergo atomic fission. In this process there are formed two simpler elements (which are initially radioactive), one to three neutrons, and a very large amount of energy.

9. Fissionable material, if subjected to neutrons in masses which exceed a certain critical size, disintegrates in a chain reaction of explosive violence. This is the basis for the atomic bomb.

0. The atomic bomb utilizes the energy of atoms by the process of fission. In this process there is an actual conversion of mass into energy. The amount of energy available far exceeds that available to man in any other form.

1. The use of atomic energy for power presents many difficulties which will probably not be overcome by scientists in less than a quarter of a century.

2. The most significant new application of atomic fission is the production of numerous kinds of radioactive elements, such as carbon-14, which find many applications in medicine as therapy agents and in the physical sciences as tracer elements.

3. The trans-uranium elements are the following:

93	:	neptunium (Np)	96	:	curium (Cm)
94	:	plutonium (Pu)	97	:	berkelium (Bk)
95	:	americium (Am)	98	:	californium (Cf)

These are all true synthetic elements.

4. The number of elements is now known to total 98. These elements occur in approximately eight hundred different forms called isotopes. The elements of very high atomic number with very few exceptions have very short periods of half-life. For this reason it is not very probable that elements with atomic numbers above 94 will ever be found to occur naturally in significant amounts.

STUDY EXERCISES

1. Consider a hypothetical element of atomic number 89 and mass 230. Prepare a table similar to the following one and then indicate what would happen to the mass and the atomic number if it disintegrates with a loss of the kind of particles (one particle per atom) indicated below:

Particle(s) lost	Atomic Number	Atomic Mass
(*a*) Neutron	.....	.....
(*b*) Alpha	.....	.....
(*c*) Beta	.....	.....
(*d*) Positron	.....	.....
(*e*) Alpha and a beta	.....	.....

2. Prepare a chart similar to that indicated below. In the appropriate column

indicate the composition of the nucleus and the arrangement of the planetar electrons for atoms of each element. Note the example which is given.

Element	Nucleus	Planetary Electrons				
		K	*L*	*M*	*N*	*O*
$^{32}_{16}S$	16p 16n	2	8	6		
$^{12}_{6}C$						
$^{14}_{6}C$						
$^{35}_{17}Cl$						
$^{37}_{17}Cl$						
$^{24}_{11}Na$						
$^{39}_{19}K$						
$^{84}_{36}Kr$						
$^{16}_{8}O$						
$^{17}_{8}O$						

3. (*a*) How can you account for the identical chemical properties of chlorine-3 and chlorine-37?
   (*b*) How can you account for the similarities in chemical properties of sulfu and oxygen, and of sodium and potassium?
4. What is the present currently accepted hypothesis for the source of th energy from the sun?
5. (*a*) Indicate the nature of the changes that occur when ordinary salt whic contains sodium-23, is bombarded with (1) high velocity deuterons an (2) exposed to slow neutrons.
   (*b*) Indicate the nature of the radioactive change that occurs in radioactiv sodium.
   (*c*) What advantages does therapy with radioactive sodium have ov radium therapy?
6. Make clear the distinction between atomic fission and a uranium or pluto ium chain reaction.
7. What three different mass effects occur during the explosion of an atom bomb?
8. What are some of the intrinsic difficulties in the production of power by th process of atomic fission?
9. What are some of the beneficent effects of the utilization of atomic energy
10. Radioactive sodium has a period of half-life of 14.8 hours. Imagine yo were the possessor of 0.001 mg of radioactive sodium. What weight radioactive sodium would you possess at the end of 74 hours?

1. (*a*) Ordinary nitrogen when treated with slow neutrons forms an unstable product which disintegrates with the formation of protons. What radioactive element must result from this series of changes?

   (*b*) One of the isotopes of boron ($^{11}_{5}B$) when bombarded with alpha particles forms two kinds of particles, one of which is protons. What radioactive element must result from this series of changes?

2. If 0.001 gram of mass could be annihilated, how much energy in ergs is created? How many calories of heat would be liberated? Note: 4.185×10^7 ergs = 1 calorie.

FOR FURTHER READING

1. Smyth, H. D., *Atomic Energy for Military Purposes.* Princeton, N. J.: Princeton University Press, 1946. (May also be obtained from Government Printing Office, Washington, D.C.)

   This is the famous official War Department report on the development of the atomic bomb under the auspices of the United States Government, 1940–45. It is a fascinating account of the atomic bomb project, written for the general reader. Chapter I, which deals with the modern conception of matter, is especially recommended. Chapter II deals with atomic fission and the problems involved in the production of plutonium.

2. Solomon, Arthur K., *Why Smash Atoms?* Cambridge, Mass.: Harvard University Press, 1946.

   The material in this volume is covered in three sections, "What is the Atom?," "How Smash the Atom?," and "Why Smash the Atom?" Emphasis is placed upon the actual experimental procedures that have been used in studying the nuclei of the atoms. There are many excellent photographs of machines, such as the fog-track apparatus, cyclotron, etc., used in nuclear research. This is one of the best books written in this field for the general reader.

3. Hecht, Selig, *Explaining the Atom.*

   Atomic fission and the atomic bomb are discussed in Chapters V to VIII inclusive.

4. Campbell, John W., *The Atomic Story.*

   Part Two deals with the atomic bomb, including some of the details of its manufacture and use. Part Three has an excellent discussion on the significance of the atomic bomb in regard to possible future wars and future world politics.

5. Taylor, H. S., Irving Langmuir, and Ernest O. Lawrence, *Molecular Films, the Cyclotron, and the New Biology.* New Brunswick, N.J.: Rutgers University Press, 1942.

   Pages 63–95 have a very interesting report by the inventor of the cyclotron, Dr. E. O. Lawrence, on the use of radioactive isotopes in medicine.

6. Pollard, Ernest, and William L. Davidson, *Applied Nuclear Physics.*

   The student who becomes more than casually interested in the modern theory of matter will profit from this work. The use of artificially radioactive elements in medicine and as tracer elements in the field of zoology is discussed in Chapter 8. Chapter 10 discusses nuclear fission.

7. White, Harvey E., *Classical and Modern Physics.* New York: D. V Nostrand Co., Inc., 1940.

Chapters 39 and 40 present a very simple but authoritative discussion artificial radioactivity and atomic fission.

8. The United States Strategic Bombing Survey, *The Effects of Ato Bombs on Hiroshima and Nagasaki.* Washington: U.S. Government Pri ing Office, 1946.

The official report on the destruction wrought by Atomic Bombs Nos. 2 an The physical, lethal, and psychological effects of the bombs were studied sho after V-J Day. The report is very comprehensive with many excellent ph graphs.

9. Bradley, David, "*No Place to Hide.*" Boston: Little, Brown and Co pany, 1948.

The author is a medical man who was present as a "Geiger counter mo at Bikini Atoll when the fourth and fifth bombs were detonated. The gr effectiveness of the bombs is undeniably demonstrated.

28

Periodic Classification of the Elements

NE OF THE MOST IMPORTANT RESULTS of the building of any science is the reat economy of mental effort resulting from the organization of a huge lass of observations, experiments, and facts into a unique whole, which ermits the discovery of general principles or scientific laws and theories iat serve as a guide in solving particular problems. The layman venturg into the field of chemistry is often bewildered by the chemist's range of iformation. All matter is composed of about ninety-five elements, or ombinations of these. These in turn have more than five hundred otopes. Many elements exist or are principally useful in their elementary ate; others are useful chiefly in the form of compounds. No one knows ie number of compounds that can occur as the result of various combinaons among the known elements. The element carbon alone has already rnished over half a million compounds for classification and study, and iis is but a fraction of the possible compounds of carbon that remain be prepared or discovered. How, then, can the exploring chemist find s way about with certainty and assurance in this maze of factual material? he answer is found in one of the most important generalizations of the iysical sciences — the periodic classification of the elements. When the search chemist sets out to develop or discover a better refrigerant than nmonia or sulfur dioxide for home refrigerators, the periodic classification the elements serves him as a guide. From many standpoints the best frigerant now available is a compound known as *dichlorodifluoromethane*, scussed more fully on page 527. This was discovered during a proam of research made possible by a knowledge of the Periodic Table. ere is but a single illustration of how the Periodic Table has enormously nplified the study of matter for the scientist.

As is true of all generalizations based upon facts, the facts had to come st. Modern chemistry dates from the time of Lavoisier. (Refer to page 6.) By 1840 enough facts concerning the elements and their comunds had been unearthed to make possible some beginnings in the task systematizing the study of the elements. During the eighteen-sixties ewlands, an English scientist, for example, had discovered the Law of

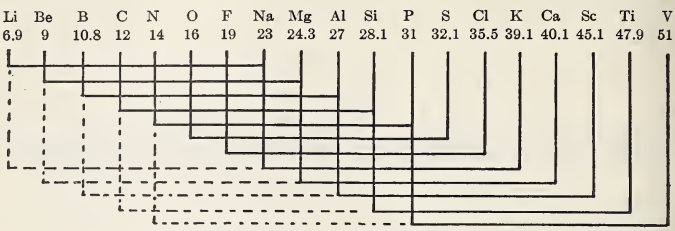


FIGURE 304. NEWLANDS' LAW OF OCTAVES

Octaves. Newlands noticed that when the elements were arranged in t order of their atomic weights, every eighth element had similar prope ties. Refer to Figure 304, which serves to indicate that lithium, sodiu and potassium have similar properties; beryllium, magnesium, and calciu have similar properties; and so have carbon, silicon, and titanium. The elements likewise form analogous compounds. Consider the followi examples:

(*a*) Carbon tetrachloride	CCl_4	All liquids relatively volatile, den
Silicon tetrachloride	$SiCl_4$	than water, insoluble in water, etc.
Titanium tetrachloride	$TiCl_4$	
(*b*) Lithium nitrate	$LiNO_3$	White solids, very soluble in wat
Sodium nitrate	$NaNO_3$	can be used in explosives, give char
Potassium nitrate	KNO_3	teristic colors to a flame, etc.

Newlands' ideas were derided as an attempt to bring "music into scienc because the law of octaves did not seem to be a discovery of any gre significance. But facts concerning the elements and their compoun continued to be discovered. In 1869, these made possible the derivati of the Periodic Law of the Elements by Mendeleef in Russia and Loth Meyer in Germany. These two scientists independently came to the sa discovery. But Mendeleef actively championed the usefulness of the l and is therefore usually given the greater share of the credit. Mendel realized that there were gaps in his Periodic Table, which he correctly a tributed to undiscovered elements. He was bold enough to predict the d covery of certain elements and even to list their characteristics in advan of their discovery. In 1871, for example, he foretold the existence of *ek silicon.* It was discovered in 1886 by Winkler in Germany and nam *germanium.* A comparison of the predicted properties with those fou upon discovery is shown in Table 40. This was remarkable evidence of t validity and usefulness of the Periodic Table.

TABLE 40

	Predicted by Mendeleef Eka-silicon (1871)	Found by Winkler Germanium (1886)
Atomic weight	72	72.6
Specific gravity	5.5	5.469
Color	Dirty gray	Grayish white
Specific gravity of the chloride	1.9	1.887

Mendeleef's first form of the Periodic Table, based upon the order of ıcreasing atomic weights, was published in 1869. Our present periodic ıbles differ in certain details; but the basic idea is still the same, namely, ıat the properties of the elements, both physical and chemical, are *periodic ınctions* of a fundamental property, the *atomic number.* This in fact is a ɔncise statement of the Periodic Law.

Modern Arrangement of the Table

Beginning with helium (atomic number 2) the elements are arranged orizontally until eight have been recorded — helium to fluorine. The ɛason for the gap will be soon apparent. In this series the number of lectrons increases regularly from two for helium to seven for fluorine. 'hese electrons are arranged with two in the K energy level and the alance in the L level. Element 10 is an inert gas and is placed under elium, and then a second series is built up with elements 10 to 17, which chlorine. Thus are formed two short horizontal series of eight elements ach. Element 18, argon, is another inert gas, and is placed under neon s the start of a first long series of eighteen elements, which ends with lement 35, bromine. Note that the K and L levels are complete in the ɛnse that there is no further increase in the number of electrons. Beginning ith element 21, however, the number of electrons in the M level increases ntil they total eighteen in copper. The increase in electrons beyond this lement goes into the fourth or N level. The series ends with bromine hich has 7 electrons in the outside N level, just as chlorine has 7 electrons ı the outside M level. Elements 36 to 53 form a second long series of ighteen elements, and 54 to 85 form a long series of thirty-two elements hich includes the group of elements known as the rare earths beginning ith lanthanum (57).

In Chapter 25 it was shown that the neutron and proton are important nit particles in building atoms. The neutron and hydrogen are placed t the beginning of the Periodic Table as elements 0 and 1. Note also ıat a whole group of elements of atomic numbers 57 to 71, inclusive, are sted as a separate series at the bottom of the table. These are the rare earths," which are indeed very rare. They have little significance ı our present story. Similarly, elements 89 to 96 are listed separately as ıe "actinide series" and contain the trans-uranium elements discovered ıce 1940. Here, too, are found uranium and plutonium, which are of ıch great significance in connection with nuclear energy. Elements 43 technetium), 85 (astatine), and 87 (francium) are the newest additions ɔ the Periodic Table. Not enough of these elements have yet been repared synthetically to permit an accurate determination of their atomic eights.

After the elements are arranged in this order (Figure 305) certain haracteristic vertical groupings occur. One vertical group contains all

FIGURE 305

PERIODIC CHA

(RE

0	LIGHT METALS IA	LIGHT METALS IIA	HEAVY METALS — BRITTLE IIIB	IVB	VB	VIB	VIIB	V
n 1.009								1
INERT GASES								
2 **2 He** 4.003	2, 1 **3 Li** 6.940	2, 2 **4 Be** 9.02						
2, 8 **10 Ne** 20.183	2, 8, 1 **11 Na** 22.997	2, 8, 2 **12 Mg** 24.32						
2, 8, 8 **18 A** 39.944	2, 8, 8, 1 **19 K** 39.096	2, 8, 8, 2 **20 Ca** 40.08	2, 8, 9, 2 **21 Sc** 45.10	2, 8, 10, 2 **22 Ti** 47.90	2, 8, 11, 2 **23 V** 50.95	2, 8, 13, 1 **24 Cr** 52.01	2, 8, 13, 2 **25 Mn** 54.93	2, 8, 14, 2
2, 8, 18, 8 **36 Kr** 83.7	2, 8, 18, 8, 1 **37 Rb** 85.48	2, 8, 18, 8, 2 **38 Sr** 87.63	2, 8, 18, 9, 2 **39 Y** 88.92	2, 8, 18, 10, 2 **40 Zr** 91.22	2, 8, 18, 12, 1 **41 Cb** 92.91	2, 8, 18, 13, 1 **42 Mo** 95.95	2, 8, 18, 13, 2 **43 Tc**	2, 8, 18, 15, 1
2, 8, 18, 18, 8 **54 Xe** 131.3	2, 8, 18, 18, 8, 1 **55 Cs** 132.91	2, 8, 18, 18, 8, 2 **56 Ba** 137.36	**57-71** See Lanthanide Series	2, 8, 18, 32, 10, 2 **72 Hf** 178.6	2, 8, 18, 32, 11, 2 **73 Ta** 180.88	2, 8, 18, 32, 12, 2 **74 W** 183.92	2, 8, 18, 32, 13, 2 **75 Re** 186.31	2, 8, 18, 32, 14, 2
2, 8, 18, 32, 18, 8 **86 Rn** 222	2, 8, 18, 32, 18, 8, 1 **87 Fr**	2, 8, 18, 32, 18, 8, 2 **88 Ra** 226.05	**89-96** See Actinide Series					

LANTHANIDE SERIES (Rare Earth Elements)	2, 8, 18, 18, 9, 2 **57 La** 138.92	2, 8, 18, 19, 9, 2 **58 Ce** 140.13	2, 8, 18, 20, 9, 2 **59 Pr** 140.92	2, 8, 18, 21, 9, 2
ACTINIDE SERIES	2, 8, 18, 32, 18, 9, 2 **89 Ac** 227±	2, 8, 18, 32, 19, 9, 2 **90 Th** 232.12	2, 8, 18, 32, 20, 9, 2 **91 Pa** 231	2, 8, 18, 32, 21, 9, 2

THE ELEMENTS

1949)

NON METALS

LOW MELTING

	VIII	IB	IIB	IIIA	IVA	VA	VIA	VIIA
				2 3 — 5 B 10.82	2 4 — 6 C 12.010	2 5 — 7 N 14.008	2 6 — 8 O 16.000	2 7 — 9 F 19.00
				2 8 3 — 13 Al 26.97	2 8 4 — 14 Si 28.06	2 8 5 — 15 P 30.98	2 8 6 — 16 S 32.06	2 8 7 — 17 Cl 35.457
	2 8 16 2 — 28 Ni 58.69	2 8 18 1 — 29 Cu 63.57	2 8 18 2 — 30 Zn 65.38	2 8 18 3 — 31 Ga 69.72	2 8 18 4 — 32 Ge 72.60	2 8 18 5 — 33 As 74.91	2 8 18 6 — 34 Se 78.96	2 8 18 7 — 35 Br 79.916
	2 8 18 18 — 46 Pd 106.7	2 8 18 18 1 — 47 Ag 107.880	2 8 18 18 2 — 48 Cd 112.41	2 8 18 18 3 — 49 In 114.76	2 8 18 18 4 — 50 Sn 118.70	2 8 18 18 5 — 51 Sb 121.76	2 8 18 18 6 — 52 Te 127.61	2 8 18 18 7 — 53 I 126.92
	2 8 18 32 17 1 — 78 Pt 195.23	2 8 18 32 18 1 — 79 Au 197.2	2 8 18 32 18 2 — 80 Hg 200.61	2 8 18 32 18 3 — 81 Tl 204.39	2 8 18 32 18 4 — 82 Pb 207.21	2 8 18 32 18 5 — 83 Bi 209.00	2 8 18 32 18 6 — 84 Po 210 ±	2 8 18 32 18 7 — 85 At

2 8 18 23 9 2 — 62 Sm 150.43	2 8 18 24 9 2 — 63 Eu 152.0	2 8 18 25 9 2 — 64 Gd 156.9	2 8 18 26 9 2 — 65 Tb 159.2	2 8 18 27 9 2 — 66 Dy 162.46	2 8 18 28 9 2 — 67 Ho 164.94	2 8 18 29 9 2 — 68 Er 167.2	2 8 18 30 9 2 — 69 Tm 169.4	2 8 18 31 9 2 — 70 Yb 173.04	2 8 18 32 9 2 — 71 Lu 174.99
2 8 18 32 23 9 2 — 94 Pu 238 ±	2 8 18 32 24 9 2 — 95 Am 242 ±	2 8 18 32 25 9 2 — 96 Cm 243 ±							

Adapted with permission from chart published by Merck & Co.

the stable elements, all of which are gases and chemically inert. The are collectively referred to as the "inert gases." The unusually stab electron groupings have already been discussed (page 490). Then the are vertical groupings which contain elements with one or more electro than are found in the preceding inert gases. Atoms of these elements they "lose" these electrons form positive ions with electronic structur like those of the nearest inert gases. These are in the columns label I A and II A. Also there are elements in Groups V A, VI A, and VII which, when they "gain" one or more, form negative ions with structur similar to the adjacent inert gas.

Elements which form ions by gaining or losing a few electrons to for an outside stable grouping of eight electrons are called *main group* elemen and are designated in Figure 305 with the letter A. The ions have stru tures similar to the inert gases. The elements within these groups for ions of the same charge. Thus the ions of Group I A are always *plus on* and *plus two* for Group II A. Similarly the negative ions of Group VII are always *minus one*, but *minus two* for Group VI A. The elements at th left of the table are *metals*, but those on the right side are *non-metal* Note that main group elements invariably gain or lose electrons to for ions in compounds which always have eight electrons in the outside she just as in the case of the inert gases.

The vertical groups of elements are often referred to as families elements. Some of these family names are listed below:

Inert gas family		Nitrogen family	Group V A
Alkali family	Group I A	Sulfur family	Group VI A
Alkaline earth family	Group II A	Halogen family	Group VII A

In the Periodic Table, however, there are many elements with as man as eighteen electrons in the next to the outer electron energy level. Thu consider silver: $_{47}$Ag 2, 8, 18, 18, 1. Furthermore, many of these elemen can lose electrons from both the outer and the next to the outer energ level, as in the case of iron:

$$_{26}\text{Fe } 2, 8, 14, 2 \longrightarrow [\text{Fe } 2, 8, 14]^{++} + 2\,e$$
$$_{26}\text{Fe } 2, 8, 14, 2 \longrightarrow [\text{Fe } 2, 8, 13]^{+++} + 3\,e$$

Elements with structures and behavior such as silver and iron are calle sub-group elements and are designated by the letter B. Note in th Periodic Table there are the sub-group elements I B to VII B inclusive. A the elements in a main group, as in Groups I A and II A, will have man similar properties. Likewise the elements in a sub-group, as I B and II B will have many similar properties. However, the main group elemen will have few properties in common with sub-group elements. Thu potassium and sodium are similar, but potassium and silver are dissimila

The foregoing considerations then have resulted in dividing the periodic ble into the following vertical groupings or families:

Main groups I A to VII A
Sub-groups I B to VII B,
Group VIII, and the
Inert gases.

It has long been customary to refer to certain groups of elements, due similarities in properties, by natural groupings within the Periodic ıble. Thus Groups I A and II A are often referred to as the *light metals.* nilarly the *non-metals* occur in a grouping by themselves. Between ese two groups are the important *heavy metals.* The properties of Group II are unique in many ways; this group is often called the *iron-platinum* oup. With the development of nuclear energy, the rare earth elements 7 to 71) are now usually referred to as the *lanthanide* series, as elements to 96 are now called the *actinide* series. In a later chapter it will be inted out that carbon and silicon have very special properties as non- etals and are also considered as a unique grouping in the Periodic Table. ter it will be pointed out that carbon is the basic element in the animal ngdom, while silicon is the basic element in the mineral kingdom.

Horizontally, there are two short series of eight elements and two long ies of eighteen, a series of thirty-two which contains the rare earth ments, and an incomplete series of ten which includes the actinide ments. Each of these series brings out the meaning of "periodicity in operties." There is a distinct *decrease* in metallic character and *increase* non-metallic character within each series. In the third series, for ample, there is a gradual change from potassium as a metal to bromine a non-metal.

es of the Periodic Table

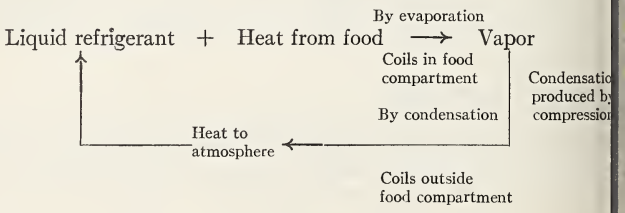
Historically, the Periodic Table has played an important part in advanc- the chemical study of matter. By use of the table the existence of rtain elements has been predicted, and the table has served as a guide in vising methods of finding these elements. The existence of germanium d gallium, of many of the rare earths, and of krypton and xenon in the ert gas family was first indicated by the Periodic Table. The table has so been of great help in the determination of the atomic weights of many the elements. When radium was first discovered, there was some doubt to whether its atomic weight was 226 or 113. If its atomic weight were 3, it would have had to be fitted into the Periodic Table between cad- um and indium. Chemically, however, it was not related to either of ese two elements. On the other hand, radium is chemically very similar barium, and it fitted very appropriately into the table below barium on e supposition that the atomic weight was 226.

The most important use of the Periodic Table is to provide a simple and

direct method for correlating the study of the elements and their co pounds and to serve as a guide in research which seeks to find new uses a applications of the elements. As has been said before, the principle volved in the use of the Periodic Table is that the properties of the eleme or of their compounds change gradually within a series or a group; the fore, unknown properties can be deduced from the position of an element the table by studying the element's neighbors. The application of t principle will be illustrated by a few examples.

1. *The Production of Non-Toxic Medicinals to Replace Toxic Arse Compounds.* Certain diseases caused by small organisms called *spiroche* can be cured by the intravenous injection of soluble organic compounds arsenic. These arsenic compounds have the disadvantage of often bei highly toxic to the patient. It was quite logical to believe, therefore, th other elements in Group V, if placed in a soluble organic molecule, mig also prove effective against spirochete organisms without being toxic the patient. Research with various organic compounds of bismuth a antimony showed that the bismuth derivatives were in many wa superior to those of arsenic. In this way organic compounds containi bismuth were perfected for use in medicine.

2. *The Development of an Improved Refrigerant for Use in Small Mecha ical Refrigerators.* The common refrigerants were at one time substanc such as sulfur dioxide, ammonia, carbon dioxide, and methyl chlori Each of these substances, however, has certain disadvantages. Mechani refrigerators operate according to the following cycle:



In the coils of the cooling compartment, heat from the food converts t liquid refrigerant to a vapor, thus cooling the food. The vaporous refr erant is then compressed to form the liquid refrigerant for use aga liberating heat which is dissipated to the atmosphere.

An ideal refrigerant should have the following properties: (1) it must non-corrosive; (2) it should absorb a large amount of heat when it eva orates; (3) it should be easily converted from a liquid to a vapor, and, v versa, in the region of room temperatures it should boil below room te perature; (4) it should be harmless if a leak should develop while in use a confined room; (5) it should be non-inflammable; (6) it should be che None of the refrigerants listed above successfully met all these standar

Except for inflammability and poisonous character, methyl chloride was satisfactory refrigerant. The starting point in the research to find a tter refrigerant was to outline an investigation which would reveal some her halogen compound of carbon that could be substituted for methyl loride. The Periodic Table was consulted for suggestions.

A clue came in the effect of the character of the halogen on the boiling int of similar compounds. This is brought out by the following data:

	Formula	Boiling point
Methyl fluoride	CH_3F	−78.0° C.
Methyl chloride	CH_3Cl	−23.7° C.
Methyl bromide	CH_3Br	4.6° C.
Methyl iodide	CH_3I	42.5° C.

ese data indicated that the boiling point increased as the atomic number the halogen increased. The boiling point of a liquid is a measure of the se of liquefying its vapor: the lower its boiling point, the more difficult is to liquefy. The boiling points of some compounds of carbon and the logens that were considered were as follows:

	Formula	Boiling point
Methyl chloride	CH_3Cl	−24° C.
Methylene chloride	CH_2Cl_2	40° C.
Chloroform	$CHCl_3$	61° C.
Carbon tetrachloride	CCl_4	77° C.
Carbon tetrafluoride	CF_4	−130° C.

us, the boiling points increased as the number of atoms of a given halogen creased. It seemed reasonable to believe, then, that the substitution of oms of fluorine for atoms of hydrogen in methyl chloride might produce a mpound to approximate the ideal refrigerant. In this hope the new sub-nce *dichlorodifluoromethane*, CCl_2F_2, was prepared and has proved to be arer the ideal than any other yet discovered. It is a very stable com-und and is non-corrosive and non-poisonous; it absorbs about thirty-ur calories during the evaporation of one gram; it boils at −19.1° C., so at it evaporates rapidly enough at refrigerator temperatures; it is con-rted back to a liquid again at a relatively low pressure (six to seven nospheres); and the cost of manufacture is not exorbitant. It is hlorodifluoromethane, which is sold under the trade name of "Freon" d which is now so extensively used in home refrigerators. This is the aterial also that is now widely used as a solvent and diffusing agent for e important insecticide "DDT."

A striking recent example of the great usefulness of the Periodic Table s its application in the determination of the properties of the trans-anium elements 93 to 96. The discovery and the determination of the operties of these elements would have been much delayed without the riodic Table. Because of the mode of formation these elements were first available in mere traces. Much of the early work on plutonium, example, was carried out with less than half a milligram of the element.

The general relationships revealed in the Periodic Table constantly guid the early research with these elements. Were these elements similar uranium or quite different? The evidence as it accumulated gradua indicated that the trans-uranium elements had structures which ma elements 92, 93, 94, 95, and 96 analogues of the rare earth elements 60, 62, 63, and 64. Compare the structure of americium, for example, w that of europium:

	K	*L*	*M*	*N*	*O*	*P*	*Q*
				s p d f	s p d f	s p d f	s
$_{63}$Eu	2	8	18	2 6 10 6	2 6 1 –	2 – – –	–
$_{95}$Am	2	8	18	2 6 10 14	2 6 10 6	2 6 1 –	2

The structures of the *Q*, *P*, and *O* energy levels of americium are simi to the *P*, *O*, and *N* levels in europium. Hence the chemical properties americium were assumed to be similar to those of europium and this w demonstrated to be true.[1] Likewise, the chemical properties of eleme 96 were found to be similar to those of element 64.

SUMMARY

1. The chemical properties and most of the physical properties of the eleme are periodic functions of their atomic numbers. This is the modern sta ment of Mendeleef's Periodic Law.
2. The vertical groups of elements in the Periodic Table, eight in number, c sist of elements which have the same number of electrons in the outer sh
3. The main or A sub-group in each vertical group consists of elements wh lose or gain electrons to form an ion with an outer shell of eight electrons si lar to that of an inert gas. The charge on the ion depends upon the numb of electrons gained or lost.
4. The B sub-group in each vertical group consists of elements with much m complex electronic structures. These elements not only lose electrons fr the outer shell, but from the next to the outside shell as well, and poss properties different from those of the A sub-group.
5. The various horizontal series in the Periodic Table — two short, three lo and one incomplete series — reveal a gradual transition in many propert from left to right in the Periodic Table.
6. Characteristic groups of elements within the Periodic Table are: (*a*) the in gases, (*b*) the light metals, (*c*) the heavy metals, (*d*) the non-metals, (*e*) t elements carbon and silicon, (*f*) the transition elements, (*g*) the radioact elements, and (*h*) the actinide series.
7. There is a distinct trend in the change from metallic (base forming) to n metallic (acid forming), from left to right within a horizontal series in t Periodic Table.
8. For the main elements within a vertical group of the Periodic Table, meta

[1] It was this similarity which suggested that element 95 be named americium for the Ameri as element 63 was named europium for Europe.

character increases with increase in atomic number; i.e., from top to bottom. With non-metals, the most non-metallic are found at the top of the groups.

The Periodic Table correlates and systematizes the immense amount of factual information concerning all the elements and their compounds, and it serves as a guide in research seeking to discover new applications of the elements and their compounds.

STUDY EXERCISES

In the column to the left are listed properties of elements, some metallic and some non-metallic. Indicate with a + or − sign which properties are associated with metals, and which with non-metals.

Properties	Metals	Non-Metals
(*a*) Conduct heat readily.		
(*b*) Often very ductile.		
(*c*) Conduct electricity readily.		
(*d*) Form oxides which with water form bases — solutions which turn litmus blue.		
(*e*) Form oxides which with water form acids.		
(*f*) Often malleable.		
(*g*) Often brittle.		
(*h*) Have a common characteristic luster.		
(*i*) Readily gain electrons.		
(*j*) Readily lose electrons.		
(*k*) Act as oxidizing agents.		
(*l*) Act as reducing agents.		

Refer to Periodic Table on pages 522–523.

The properties of the elements listed below vary in a regular manner within a *series* or within a *group*. By means of a check mark, indicate how each property varies within the Periodic Table. Question (*a*) is answered to serve as a pattern. For nearly all, two checks should be given.

Variation	Left to Right	Right to Left	Top to Bottom	Bottom to Top
(*a*) Atomic number increases.	✓		✓	
(*b*) Atomic weight increases.				
(*c*) Number of valence electrons increases.				
(*d*) Tendency to lose electrons increases.				
(*e*) Tendency to gain electrons increases.				
(*f*) Metallic character increases.				
(*g*) Atomic volume increases.				
(*h*) Tendency to become radioactive increases.				
(*i*) Number of electronic shells increases.				
(*j*) Oxidizing ability increases.				
(*k*) Reducing ability increases.				
(*l*) Non-metallic character increases.				

3. What explanation can be offered to account for the difficulty that has bee encountered in finding elements 85 and 87?
4. Tungsten (No. 74) is used to make filaments in electric light bulbs. Und certain conditions it is ductile and has a melting point of 3370° C. Woul you venture an opinion that tantalum (No. 73) might also be used f making bulb filaments? Explain.

FOR FURTHER READING

1. Hatcher, W. H., *An Introduction to Chemical Science.* New York: Joh Wiley and Sons, 1940.
   The history and usefulness of the periodic law is treated in Chapters XV XVII, and XVIII.
2. "Periodic Law," *Encyclopedia Britannica,* 14th edition, XVII.
   This article is for the general reader. For our purposes the paragraph dealin with the transition series in the Periodic Table can be omitted.

29

The Combination of Atoms

THE END of Chapter 22, dealing with combustion and chemical changes, question was raised concerning the forces that hold the atoms in com- nds together. It was shown that the stuff of which the myriad things t fill the world are composed can be reduced to no more than about ety different kinds of elements. By combining chemically, in definite os by weight, the relatively few elements have formed the thousands of npounds which are either found in nature or produced by the efforts of n. Chemical reactions may be generally considered to follow collisions nolecules. In these collisions the molecules disrupt and the resulting ms recombine to produce new kinds of molecules, or, as we say, new npounds. This concept of chemical reactions does not explain why ms combine at all, or how they manage to stick together after the com- nd is formed. Why, for example, should one atom of oxygen combine h two atoms of hydrogen to form water, H_2O, and two atoms of oxygen h one of carbon to form carbon dioxide, CO_2? Atoms, according to the y chemists, were hard, small ball-like structures which had for each er a peculiar type of attraction which was called "chemical affinity" ough which they were assumed to combine with each other. Since mical affinity could not be explained, the scientific imagination of the — particularly of beginners — endowed the ball-like atoms with ks. Oxygen was assumed to have two centers of affinity (or two hooks), hydrogen only one. Hence it required two hydrogen atoms to fully sfy oxygen.

n order to explain both the manner in which atoms combine and the es that hold them together in the molecules, it became necessary to mine a large amount of experimental evidence about the ultimate na- of matter. It has been shown in previous chapters that the atom is a miniature solar system, with the positive nucleus as the "sun" and n the negative electrons revolving about it in planetary fashion; further, t the electrons revolve in different orbits and are held by the positive rge of the nucleus. Of these electrons, those that are held with ap- ximately equal forces are grouped together in the same *electron shell.*

The combining capacity of an atom is assumed to be a function of t outer or *valence electrons*, for they provide, so to speak, the mortar of atom combinations. The present chapter deals with the explanation of the mo important types of atomic union in terms of the electronic structure of t atom.

Types of Elements

The total number of known elements, including those found in natu either in the combined or free form and those prepared by nuclear tran formations, is ninety-six. For the purpose of study, the elements can classified in three general types: the *inert gas type*, the *metal type*, and t *non-metal type*.

The Inert-Gas Type. At the time the Periodic Table was formulat (1860–1865) the inert gases were not known. In 1868, Lockyer found ev dence for the existence of an element in the sun not then known to exist the earth. He called it helium (*helios* — sun). As described in greater d tail on page 572, helium was identified on the earth by Sir William Rams in 1895. The year before Ramsay had found argon in the air — less tha one per cent by volume. In rapid succession, Ramsay found neon, kry ton, and xenon.

The arrangement in energy levels of the planetary electrons in the ine gases is given in Table 41. The inert gases are unusual in that they exhib an almost total lack of chemical properties: they show practically no ten ency to react with themselves or with other elements to form compound They are chemically inert. They are also very difficult to ionize in co trast to other elements, such as hydrogen, sodium, and chlorine, whi exhibit marked chemical behavior. This stability or inertness is assum to be dependent on their particular planetary groupings. They represe extraordinarily stable systems in the sense that they tend neither to tran fer nor share electrons. With the exception of helium, each of them h eight electrons in the outside shell.

TABLE 41. THE STRUCTURE OF THE INERT GASES

Element	Atomic Number	Energy Level					
		1 K	2 L	3 M	4 N	5 O	6 P
Helium	2	2					
Neon	10	2	8				
Argon	18	2	8	8			
Krypton	36	2	8	18	8		
Xenon	54	2	8	18	18	8	
Radon	86	2	8	18	32	18	8

The Metal Type. In this group hydrogen is included. These elemen are characterized by possession of a few more electrons than would be four

an inert-gas structure. For example, lithium may be compared with lium, magnesium with neon, and potassium with argon:

$_{2}$He 2	$_{3}$Li 2, 1
$_{10}$Ne 2, 8	$_{12}$Mg 2, 8, 2
$_{18}$A 2, 8, 8	$_{19}$K 2, 8, 8, 1

iis notation means that magnesium, for example, has 12 for its atomic mber — indicated by the subscript 12 — and that it has two electrons the first energy level, eight in the second, and only two in the third. ie electrons in the outer, incomplete shell are loosely held and are referred as the valence electrons. Magnesium atoms are much easier to ionize collision with electrons in a cathode ray tube than is neon. These outer ctrons are so loosely held that they move through the metal when is connected to a source of electricity; that is, metals are electrical nductors. The chemical activity of the metals is ascribed to the fact at they tend to give up these electrons to other substances so as to become ns in which the electron arrangement is similar to that found in the inert ses. Chemically speaking, the ions of the more active metals are latively inactive. We can schematically represent the formation of agnesium ion as follows.

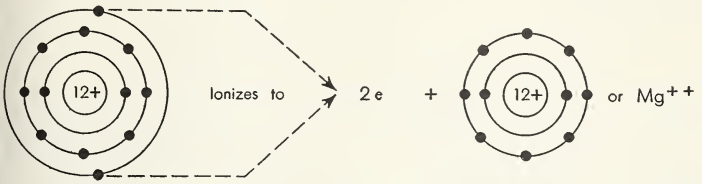


FIGURE 306

ote that the electronic structure of the magnesium ion, Mg^{++}, is identical th that of the neon atom. The formation of a magnesium ion can occur rough collision with an electron in the gaseous condition, or in the solid ate by having something present to "capture" its electrons.

Non-Metal Type. Oxygen, chlorine, and sulfur are typical non-metals. ie structure of these elements is indicated below:

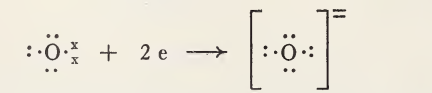
$_{8}$O 2, 6 $\quad :\ddot{O}\cdot^{x}_{x}$ $\qquad$ $_{17}$Cl 2, 8, 7 $\quad :: \cdot\dot{Cl}\cdot :^{x}$

$_{16}$S 2, 8, 6 $\quad :: \dot{S} \cdot :^{x}_{x}$

Note — The x's represent gaps in an energy level.

The non-metals lack a few electrons toward having their shells complete the outer energy levels, and their atoms become more stable by captur-

ing rather than losing electrons. The great chemical activity of oxyge which is two electrons short of a complete octet, is associated with t tendency it shows in capturing two electrons, to form a negative ion simil in structure to neon except for its negative charge of 2:



An atom of chlorine gains one electron to form the chloride ion, whi sulfur can capture two electrons to form the sulfide ion. Each ion relatively inert and, chemically speaking, similar to neon and argon.

The preceding formulas are commonly abbreviated by showing only t electrons in the outer shell of the atom. These outer electrons are ord narily the only ones that participate in chemical reactions, and they a called *valence electrons*. They are shown by a corresponding number dots around the symbol, which represents the remainder of the ato This remainder of the atom, consisting of the nucleus and all occupi electron shells except the outermost, usually remains unchanged in chemic reactions, since it resembles the electronic structure of an inert gas. T following illustrates the formation of ions by both metallic and no metallic atoms:

Table 42. Formation of Ions by Both Metallic and Non-Metallic Atoms

Element	Electronic Structure		Electronic structure inert gas identical wi that of the ion
	Atom	Ion	
Magnesium Mg	$_{12}$Mg 2, 8, 2 or Mg:	$_{12}$Mg 2, 8 or Mg^{++}	Neon (2, 8)
Potassium K	$_{19}$K 2, 8, 8, 1 or K·	$_{19}$K 2, 8, 8 or K^{+}	Argon (2, 8, 8)
Oxygen O	$_{8}$O 2, 6 or :Ö:	$_{8}$O 2, 8 or $[:\ddot{O}:]^{=}$	Neon (2, 8)
Chlorine Cl	$_{17}$Cl 2, 8, 7 or :Cl·	$_{17}$Cl 2, 8, 8 or $[:\ddot{Cl}:]^{-}$	Argon (2, 8, 8)

In the above formulas the dots represent the electrons of the valence she The plus and minus charges which are placed on the symbols representi the ions indicate the net charges due to the deficiency or excess of electro on the ionic structure as compared with the number in the neutral ato

Combination of Atoms by Sharing Electrons

The theory of chemical combination is based on experimental eviden

esented by the behavior of the large number of chemical compounds, th those which occur in nature and also those which have been nthesized in the laboratory by the chemist. Consider, for example, two mpounds: sodium chloride — common table salt — and carbon tetra- loride, often used in dry cleaning. Both contain chlorine. The physical d chemical properties of these compounds are entirely different, as will shown in a later section. Since the two compounds are combinations the atoms sodium and carbon with the atom of chlorine, the inference is at chlorine must combine in a different manner with sodium than with rbon. The theory of combination of atoms attempts to explain that e difference in properties between the two compounds is due to the ference in the type of union or *chemical bond* by which the atoms are mbined in each compound.

The starting point of the theory is the electronic configuration of the oms of the inert gases shown in Table 41, page 532. Since these atoms not combine, and hence are relatively stable as compared with the oms of the other elements, it is assumed that when atoms combine they nd to acquire the electronic configuration of an inert gas. Consider, for ample, the element carbon whose electronic configuration may be written us:

$$^{12}_{6}\mathrm{C}\ 2, 4 \quad \text{or} \quad \cdot\dot{\underset{\cdot}{\mathrm{C}}}\cdot$$

cording to this concept, when an atom of carbon combines it attracts ar its outermost electronic orbit four electrons, so that its electronic nfiguration is similar to the inert gas, neon (2, 8). Therefore the number atoms of an element, A, with which one carbon atom will combine pends on the number of valence electrons which the atom A possesses. it has one, as is the case with hydrogen, it will take four atoms of hydro- n to combine with an atom of carbon. Accordingly the union can be presented thus:

$$\underset{\text{Carbon}}{1\,\mathrm{C}} + \underset{\text{Hydrogen}}{4\,\mathrm{H}} \longrightarrow \underset{\text{Methane}}{\mathrm{CH_4}}$$

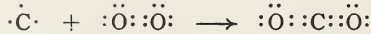
terms of the electron theory, the atoms combine by sharing their valence ctrons:

$$4\,\mathrm{H}\cdot + \cdot\dot{\underset{\cdot}{\mathrm{C}}}\cdot \longrightarrow \mathrm{H}:\overset{\mathrm{H}}{\underset{\mathrm{H}}{\overset{\cdot\cdot}{\underset{\cdot\cdot}{\mathrm{C}}}}}:\mathrm{H}$$

4 atoms 1 atom 1 molecule

ch carbon atom contributes four electrons, and each hydrogen atom ntributes one, forming four stable pairs of electrons which act as the rce of attraction between the nuclei of the atoms. It will be noted that

the carbon atom in sharing electrons with four hydrogen atoms has acquire the neon (2-8) electron configuration, while each hydrogen atom h acquired the helium (2-) configuration. In this manner both carbon ar hydrogen have attained the outer stable electronic configuration of a inert gas. In a similar manner, oxygen, with an electronic configuratio of 2-6, combines with carbon, forming four pairs of electrons shared betwee the carbon and the two oxygen atoms as shown in the following formula

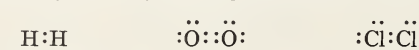


Carbon Oxygen Carbon dioxide

It will be noted that each atom acquires a complete eight-electron she counting its own electrons and those which it shares with the other ator

By far the largest number of known chemical compounds are assume to be formed by the electron sharing or *covalent bond.* This is particular true of the carbon and silicon compounds, which constitute the large group of known chemical compounds. It will be noted that carbon ar silicon each have four electrons in the outer shell.

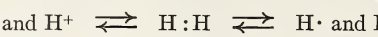
Union by covalent bonds is not restricted to unlike atoms such a carbon and hydrogen or carbon and oxygen; two atoms of hydrogen oxygen or chlorine may unite by sharing electrons to form stable molecule



$H:H$	$:\ddot{O}::\ddot{O}:$	$:\ddot{Cl}:\ddot{Cl}:$
H_2	O_2	Cl_2
Hydrogen Molecule	Oxygen Molecule	Chlorine Molecule

This mode of union prevails in the molecules of most elements in th gaseous state. It will be noted in the representation of the molecules th the electron arrangement is such that the outer shell bears resemblan to the outer electron structure of an inert gas.

The molecules of these gaseous elements are relatively stable, but wh heated to a high temperature may disrupt or dissociate in two ways:



Ions Molecule Atoms

The leftward tendency — that is, formation of positive and negative io — is very small; when hydrogen molecules dissociate, they usually for neutral atoms. Since the free and neutral atoms do not have an electron structure resembling an inert gas they are very active chemically and imm diately combine; here again the tendency is for the element to react a *acquire the configuration of greatest stability.*

As noted above, the tendency to unite by formation of *covalent* or *no ionic bonds* is predominant in carbon and silicon. Generally this tenden is strong if the groups in which the elements are classified in the perio

stem are not very far apart. Consider, for example, sodium (Group I) id chlorine (Group VII), and carbon (Group IV) and chlorine. The ion between chlorine and carbon in carbon tetrachloride is by means of valent bonds. The union between sodium, a typical metal, and chlorine, typical non-metal, is by means of another type of union called the *ctrovalent* or *ionic bond*. In the formation of a covalent bond each of the oms *contributes an electron* to form a pair of electrons which is then shared intly between the two. In the formation of the electrovalent bond there *transfer of electrons* from one atom to another, resulting in the formation ions.

ombination of Atoms by Transfer of Electrons

As explained in the preceding paragraphs, the metallic elements lose eir valence electrons comparatively easily to form positive ions, while e non-metallic elements tend to gain electrons and to form negative ions. eference to Table 37, page 489, shows that the active elements of the st and second group of the periodic system require less energy to lose ctrons (ionize). The formation of ions may be represented thus:

$$\mathrm{Na}\cdot \longrightarrow \mathrm{Na^{+}} + \mathrm{e}$$
$$\mathrm{Mg}: \longrightarrow \mathrm{Mg^{++}} + 2\,\mathrm{e}$$

losing electrons, these atoms become ions which have the stable con- uration of the eight-electron shell. On the other hand, the elements the seventh group, such as chlorine $\left[:\ddot{\mathrm{Cl}}\cdot\right]$ and bromine $\left[:\ddot{\mathrm{Br}}\cdot\right]$, hibit a greater tendency to accept electrons and complete a shell of eight, an to lose their outer electrons. In accepting electrons, these atoms m negative ions which are stable:

$$:\ddot{\mathrm{Cl}}\cdot + \mathrm{e} \longrightarrow \left[:\ddot{\mathrm{Cl}}:\right]^{-}$$

When sodium and chlorine are brought together there is an immediate action resulting in the formation of sodium chloride. The formation of e compound is assumed to have taken place through the transfer of an ctron from sodium to chlorine. The two unlike *charged atoms*, or ions, ite to form the compound sodium chloride. The reaction is represented symbols thus:

$$2\,\mathrm{Na}\cdot + :\ddot{\mathrm{Cl}}:\ddot{\mathrm{Cl}}: \longrightarrow 2\,\mathrm{Na^{+}} + 2:\ddot{\mathrm{Cl}}:^{-} \longrightarrow 2\,\mathrm{Na^{+}\,Cl^{-}}$$

will be noted that sodium chloride contains positive sodium ions and gative chlorine ions held together by the electrostatic force of unlike arged bodies. The crystal of sodium chloride is a cubical crystal lattice ving alternate positive sodium ions and negative chlorine ions. In other rds, it is a huge ionic aggregate. (See Figure 307.) This type of union, aracteristic of the metals of the first group and the non-metals of the

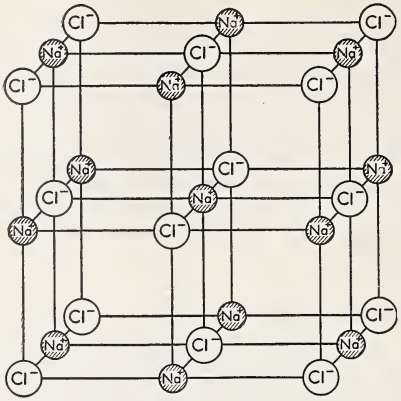


FIGURE 307. STRUCTURE OF A SODIUM CHLORIDE CRYSTAL

seventh group, is called an *ionic union* or an ionic chemical bond. It ind cates that the compound does not consist of neutral molecules but crystalline aggregates composed of charged particles. Compounds of th type consist of ions; hence they are called *ionic*.

Characteristics of Ionic and Non-Ionic Compounds

Sodium chloride ($Na^+ Cl^-$) is a solid with a very high melting poi (801° C.) and a still higher boiling point. This is due to the electrostat forces holding the ions together in the crystal of the salt. Sufficient ener has to be expended to overcome this attraction. On the other hand, carb tetrachloride (CCl_4), which is considered a non-ionic compound, is a liqu with a low melting point (−22° C.) and low boiling point (77° C.); t liquid consists of molecules which can be separated easily by small amoun of energy. Generally, ionic compounds are crystalline solids with hi melting points and boiling points, while non-ionic compounds are eith low-melting-point solids or liquids or gases.

The differences between sodium chloride and carbon tetrachloride a even more striking when their behavior toward an electric current a reagents is examined. We shall postpone a discussion of what an electr current is until Chapter 35, and it will suffice for our present discussi to state that an electric current consists in the passage of a negative char from a point where there is an excess of negative charge to a point whe there is a positive charge (or a deficiency of negative charge). Thus, Figure 308, *B* represents a battery which may be considered a pump delive ing electrons to *N*, or the negative electrode. At *P*, the positive electro there is a deficiency of electrons. If the vessel is empty and the electrod *N* and *P* are connected through a wire, the lighting of the bulb will sh

ıe passage of an electric current. If the wire is removed and the vessel filled with a liquid which contains positive and negative ions, these ill be attracted to the oppositely charged electrodes and thus a current ill pass through the liquid and it will be indicated by the lighting of the ılb, with the degree of conductivity indicated roughly by the brightness the light. For example, if only a dim red glow is obtained, the ɔnclusion is that the liquid is a very poor conductor. Carbon tetra-ılloride does not show even a dim glow, hence it is a non-conductor, a ct which agrees with the assumption that this compound is non-ionic ıd made of neutral molecules. When water is added, carbon tetra-ılloride does not appear to go to solution, and the system is ill a nonconductor.

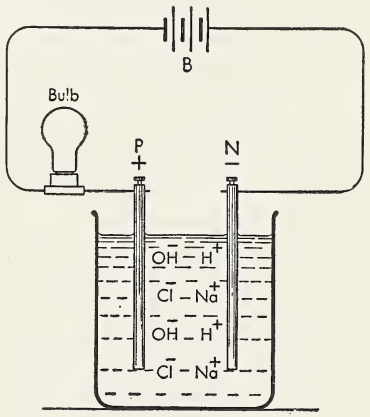


FIGURE 308

APPARATUS FOR TESTING CONDUCTIVITY OF LIQUIDS OR SOLUTIONS

Sodium chloride is a solid; when is fused to a liquid and the two ectrodes are dipped into it, the ılb shines brightly, indicating that ıuid sodium chloride is a good nductor. This agrees with the sumption that the compound is ıic. The passage of current in-ılves the attraction of the positive ıs at the negative electrode and negative ions at the positive ectrode; the changes occurring ll be discussed later. If water added, the solid sodium chloride ssolves to a certain extent. The ueous solution also conducts elec-c current, which indicates that ıter, in dissolving the crystal of sodium chloride, separates the positive dium ions and negative chlorine ions, which migrate to the poles and e there discharged.

The behavior toward chemical reagents is illustrated by the addition of solution of the reagent silver nitrate ($Ag^+ NO_3^-$). Sodium chloride mediately gives a white curdy precipitate of silver chloride ($Ag^+ Cl^-$), ıich separates out because it has a very low solubility. Carbon tetra-loride, even when boiled with a solution of silver nitrate, gives only a nt cloudiness. This agrees with the assumptions made. Sodium loride, being made up of ions, furnishes in solution chloride ions which mbine with the silver ion to form the not easily soluble silver chloride. ı the other hand, carbon tetrachloride, being made up of molecules, does t furnish any chloride ions, and hence there is no reaction. The molecule carbon tetrachloride is assumed to consist of one carbon atom which

shares its four outer electrons with four chlorine atoms to form an ele trically symmetrical molecule represented by the following formula:

The union of carbon and chlorine is assumed to take place by non-ion bonds (electron-sharing), and hence there is very little tendency for t molecule of carbon tetrachloride to form chloride ions.

It will be noted that the assumptions made about ionic and non-ion compounds explain their behavior. However, irrespective of any assum tions, experimental evidence indicates that the modes of union betwe chlorine and sodium and between chlorine and carbon are different. T modern electronic theory of atomic union explains this difference. T student is reminded, however, that electron transfer, sharing of electro dots, plus and minus charges are assumptions which help to explain a correlate the facts of the behavior of elements and compounds.

Polar and Non-Polar Molecules

It has been assumed thus far that the difference between ionic and no ionic compounds is the position of the electrons. For example, A : B assumed to be a neutral molecule, while $C^+ :D^-$ is an ionic structure. A : B the shared electron is equally attracted by both atoms and the stru ture is symmetrical and electrically neutral; such a molecule is call *non-polar*. In the structure $C^+ :D^-$, the atom D has far more attracti for electrons and hence there is an actual transfer or displacement of t electron from C to D, and these two charged particles are held togeth by electrostatic attraction.

Between these two extremes of equal sharing and complete displaceme there are a number of intermediate types of molecules in which the el trons are displaced to a small or large degree but not completely as in t ionic compounds. For example, consider H:Cl: for a moment. T chlorine atom has greater electron attraction than hydrogen, hence t electrons are displaced toward chlorine and the molecule is asymmetric in other words, it is negative on one end and positive on the other. Su molecules are called *dipolar* or simply *polar* molecules.

The polar molecules under appropriate conditions may be made m asymmetrical and pulled apart until finally the molecule dissociates a forms ions. H:Cl: in a solvent like benzene or carbon tetrachloride, whi consists of neutral molecules, does not exhibit any conductivity of curre but in a solvent like water, which is composed of asymmetrical molecul it is entirely dissociated into hydrogen ions (H^+) and chlorine ions (:Cl:

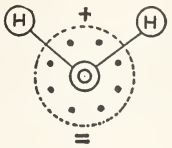


FIGURE 309 (*a*). DIAGRAM OF WATER DIPOLE

This dissociation was brought about by the environment, namely, the water molecules. Water has not a symmetrical but an asymmetrical structure, which may be roughly represented by the dipole shown in Figure 309, *a*. When hydrogen chloride molecules (H:Cl:) dissolve in water, they are surrounded by the water dipoles. At the chlorine end the dipoles have the positive side turned, and at the hydrogen end the negative side, thus weakening the force of the shared-electron pair until chlorine detaches itself as an ion carrying the extra electron. Hydrogen chloride when dissolved in benzene is undissociated, but when dissolved in water is completely dissociated, or *ionized*. The ionization of polar compounds which are essentially compounds formed by covalent bonds, into ions due to the action of the solvent should not be confused with the ionization of the salt type of compounds which are formed by ionic or electrovalent bonds. Compounds such as sodium chloride, potassium bromide, and the like already consist of ions in the solid state. When these compounds pass into the liquid state (on heating) they conduct electric current which indicates that the liquid consists of ions or ionic aggregates. Similarly, when these compounds are dissolved in such polar solvents as water, they separate completely into positive and negative ions. On the other hand, the compounds which are formed by intermediate bonds (between the

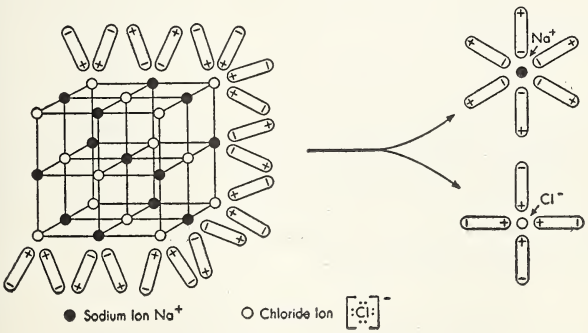


FIGURE 309 (*b*). IONIZATION OF A POLAR SUBSTANCE BY WATER DIPOLES

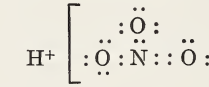
typical ionic and typical non-ionic) — that is, those which consist of polar molecules — ionize to a variable degree when dissolved in a solvent such as water; the degree of ionization depends on the nature of the atoms within the molecule or the displacement of the electrons forming the bonds, and also depends on the solvent.

Stable Atomic Groupings or Radicals

Many compounds contain both types of bonds, that is, the ionic and the covalent. For example, nitric acid is represented by the formula HNO_3. In dilute solutions it behaves as if it were made of hydrogen ions and nitrate ions, H^+ and NO^-_3; it does not behave as if it were made of hydrogen, nitrogen, and oxygen. The union of nitrogen and oxygen obviously is different from the union between hydrogen and the rest of the molecule, as can be shown by action of very dilute nitric acid on magnesium:

$$Mg + 2\,H^+NO^-_3 \longrightarrow Mg^{++}(NO^-_3)_2 + H_2$$

This can be explained by the assumption that the nitrogen and oxygen atoms, being both non-metals and in adjacent groups of the Periodic Table, unite by covalent bonds as shown in the following structure:

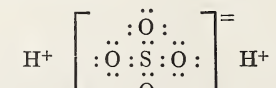


Note that the nitrate grouping has an extra electron. As shown above, the nitrate grouping or radical within the brackets has twenty-four electrons instead of the twenty-three which it would have had if uncharged (five from the nitrogen and six from each of the three oxygen atoms). The extra electron from a hydrogen atom therefore gives the nitrate radical a single negative charge. Under certain conditions the covalent bonds between oxygen and nitrogen may be broken, as when concentrated nitric acid reacts with copper:

$$Cu: + 4\,HNO_3 \longrightarrow Cu^{++} + 2\,NO^-_3 + 2\,NO_2 + 2\,H_2O$$

This type of reaction is cited to illustrate that under certain conditions the covalent bonds in radicals may be broken, and not for the purpose of discussing the type of chemical reaction between copper and nitric acid.

The same reasoning is followed in discussing the behavior of sulfuric acid, which in very dilute solutions behaves as $2\,H^+$ and $SO^=_4$, and is explained by the following structure:



The sulfate radical has thirty-two electrons instead of thirty (four oxygen atoms and one sulfur with six electrons in each of the five atoms), and therefore it has two extra electrons represented by a double negative charge. The extra electrons were donated by two atoms of hydrogen. As in the nitrate radical, the covalent bonds between oxygen and sulfur may be broken by heating the concentrated acid with copper:

$$Cu: + 2\,H_2SO_4 \longrightarrow Cu^{++} + SO^{=}_4 + SO_2 + 2\,H_2O$$

Molecules and Ions

In terms of the molecular theory, a molecule (page 407) is the smallest particle of a substance that exists in the free state as a stable, neutral particle independent of other similar particles. For example, oxygen, hydrogen, nitrogen, and many of the elementary gases exist in the free state as diatomic molecules. As previously stated, these molecules are relatively stable since they are formed by covalent or electron-sharing bonds. These molecules, however, can absorb energy and thereby become activated and ultimately dissociate into atoms. The latter, in contrast to the molecules, are very active. The reactivity in terms of the electron theory is explained as a tendency of the atom to acquire a stable electronic configuration. Since the atoms of the inert gases do not show any tendency to combine, they do not form molecules consisting of two or more atoms; their molecules are considered to be monoatomic.

Reference to page 536 will show that only compounds formed by covalent bonds or intermediate bonds between ionic and covalent can be considered to have molecular structure. For example, sodium chloride (NaCl), potassium bromide (KBr), calcium oxide (CaO), and all ionic compounds form not molecules but ionic aggregates in the form of crystalline solids. On the other hand, carbon tetrachloride (CCl_4), hydrogen chloride (HCl), water (H_2O), and methane (CH_4) form molecules which are either polar (unsymmetrical distribution of charge) or non-polar.

The vast number of chemical reactions which are constantly going on in the living and non-living (mineral) world consist to a very large extent of reactions between ions or molecules. In the case of ions, it is relatively easy to see why charged particles will attract each other, but reactions between molecules are more difficult to understand. An attempt will be made in the next chapter to discuss the more common types of chemical reactions.

SUMMARY

1. Elements are classified into three general types: inert gases, metals, non-metals.
2. Inert gases are assumed to have stable electronic configurations, and hence do not react.
3. Metals ordinarily have one to four electrons in the outer shell; they react by losing electrons to form positive ions.

4. Non-metals usually have four or more electrons in the outer shell, and they gain electrons to form negative ions.
5. The combination of elements to form compounds is explained as the combination of atoms by the sharing or gain and loss of electrons.
6. Non-ionic compounds are formed by sharing electrons; ionic compounds are formed by the gain and loss of electrons by the atoms to form ions.
7. Ionic compounds in the liquid state or in solution are conductors of electric current and generally react rapidly; non-ionic compounds do not conduct current and generally react slowly.
8. Compounds formed by sharing electrons are composed either of non-polar (electrically symmetrical) molecules or of polar (electrically asymmetrical) molecules. Polar molecules result when the combining atoms have a noticeably different attraction for the electron pairs.

STUDY EXERCISES

1. An element A has an atomic weight of 23 and an atomic number of 11. Another element B has an atomic weight of 32 and an atomic number of 16.
   (*a*) Draw a diagram showing the structure of an atom of each of these elements.
   (*b*) Are they likely to combine?
   (*c*) If they combine, what will be the formula of the compound? (AB, AB_2, A_2B, A_2B_3)
2. Underline the word in each parenthesis which makes each statement true:
   (*a*) A covalent compound is one which is formed when electrons are (shared by two atoms, gained by two atoms, transferred from one atom to another, lost by two atoms). An atom which has 6 electrons in its outer shell is likely to (lose, gain) (0, 1, 2, 3, etc.) electrons, and forms (positive, negative) ions. An atom which has 8 electrons in its outer shell is likely to (gain, lose, keep) (0, 1, 2, 3, etc.), electrons, and forms (positive, negative neutral, no) ions.
   (*b*) Two substances which easily lose electrons (are, are not) likely to combine. Two substances which easily gain electrons (may, may not) combine. If they do combine, they probably form (ionic, non-ionic) compounds by (sharing, transferring) electrons. Two substances, one of which gains, while the other loses electrons, form compounds by (sharing, transferring) electrons.
3. The following table lists the names and formulas of a number of substances. Before each, place the letter C if the chemical union between the atoms is *covalent* or *non-ionic*; I if the union between atoms is *ionic*; P if the molecule is *polar*; NP if the molecule is nonpolar. (In some cases there is more than one answer.)

.... Hydrogen, H_2
.... Methane, CH_4
.... Nitrogen, N_2
.... Potassium bromide, KBr
.... Sodium oxide, Na_2O
.... Silicon tetrachloride, $SiCl_4$
.... Water, H_2O
.... Hydrogen chloride, HCl
.... Lithium fluoride, LiF
.... Carbon tetrachloride, CCl_4
.... Magnesium chloride, $MgCl_2$

4. Give a summary as to the manner in which elements combine to form compounds. Use as examples: (*a*) A typical metal and non-metal; (*b*) a member of Group IV of the periodic system and a non-metal (see page 522). Cite experimental evidence to support the statements made.

5. Underline the letter of the formula which results from the combination of the two elements whose valence electrons are given:

(*a*) X 2; Y 7; the compound will be (A. XY; B. X_2Y; C. XY_2)
(*b*) X 3; Y 6; the compound will be (A. XY; B. X_2Y_3; C. XY_2)
(*c*) X 1; Y 6; the compound will be (A. XY; B. X_2Y; C. XY_2)
(*d*) X 4; Y 7; the compound will be (A. XY_4; B. X_2Y; C. XY_2)

6. Insert the letter *T* if true, and F if false.

.... (*a*) A covalent compound is one that is formed when electrons are shared.
.... (*b*) An atom that has 6 electrons in the outer shell is likely to lose electrons.
.... (*c*) An atom that has 6 electrons in the outer shell has a valence of 2.
.... (*d*) Two substances that easily lose electrons are not likely to combine.
.... (*e*) Two substances that easily gain electrons may combine.
.... (*f*) If substances that easily gain electrons do combine, they probably form non-ionic compounds.
.... (*g*) Ionic compounds are formed by transferring electrons.
.... (*h*) An atom that has 8 electrons in the outer shell is likely to keep its electrons.
.... (*i*) An atom that has 8 electrons in the outer shell forms no ions.

FOR FURTHER READING

1. Hildebrand, J. H., *Principles of Chemistry.*
A discussion of ionic and non-ionic compounds, polar and non-polar molecules, will be found on pages 89–95 and 292–297.

2. Babor, J. A., *Basic College Chemistry.*
A discussion of combination of atoms will be found on pages 50–55.

3. Briscoe, Herman T., *College Chemistry.*
A discussion of ionic and non-ionic compounds will be found on pages 46–48; of polar and non-polar molecules, on pages 174–176.

4. Strong, Ralph K., *Chemistry for the Executive.*
Chapter 7 gives a discussion on the structure of crystals and solids.

30

A Study of Chemical Reactions I

CHEMICAL REACTIONS are constantly occurring in nature. The growth of plants and animals and the decomposition and decay of plant and animal matter which is no longer living are familiar examples of chemical changes. It was shown in Chapter 22 that the heat produced in the animal body by which life is sustained is the product of chemical changes; however, the changes in the living cells are too complex to be studied here in detail. It will therefore be necessary to choose from the simpler types of chemical reactions in order to illustrate the principles involved.

Types of Chemical Change

Most chemical reactions can be classified into three groups: (1) those which involve a transfer or shift of electrons; (2) those which involve exchange of ions or partner exchanges; (3) complex reactions which are characteristic of organic compounds. The last type of chemical change will not be considered in any detail in this text.

1. *Reactions involving transfer or shift of electrons.* For the purpose of study, this type of reaction may be divided into three subgroups: (*a*) simple combinations which involve transfer of electrons to form ionic or electrovalent substances; (*b*) simple combinations which involve a shift of electrons to form covalent substances; (*c*) simple replacement reactions which involve either electron transfer or electron shift.

The union between a metal like sodium and a non-metal like chlorine was cited in the preceding chapter as an illustration of union between atoms by transfer of electrons. This type of reaction illustrates the simple combination to form an ionic or electrovalent substance. In such reactions the metallic atom loses electrons while the non-metallic atom gains electrons. Another example of this type is the burning of magnesium in oxygen. The magnesium atom loses two electrons to form a doubly charged positive ion while oxygen gains electrons to form a doubly charged negative ion. This kind of reaction, involving union with oxygen, was earlier called *oxidation*; oxygen which gained electrons was called an *oxidizing agent* or

oxidant. The following example illustrates this type of simple combination:

Magnesium + oxygen ⟶ Magnesium oxide

$$2\,Mg: + :\ddot{O}::\ddot{O}: \longrightarrow 2\,Mg^{++} \left[:\ddot{O}:\right]^{=}$$

reducing agent — oxidizing agent — positive ion — negative ion

The equation may be simplified and written thus:

$$2\,Mg + O_2 \longrightarrow 2\,Mg^{++}\,O^{=}$$

Both the magnesium atom and oxygen molecule are regarded as neutral, since each atom has as many planetary electrons as protons in its nuclei.

By similar equations other simple combinations of metals and non-metals to form ionic substances are illustrated below. In all of these a typical metal *loses* electrons (acts as a *reducing agent*) and forms a positive ion while the non-metal *acquires* electrons (acts as an *oxidizing* agent) and forms a negative ion.

Calcium + Chlorine ⟶ Calcium chloride

$$Ca + Cl_2 \longrightarrow Ca^{++}(Cl^{-})_2$$

$$Ca: + :\ddot{Cl}:\ddot{Cl}: \longrightarrow Ca^{++}\left[:\ddot{Cl}:\right]_2^{-}$$

Zinc + Sulfur ⟶ Zinc sulfide

$$Zn + S \longrightarrow Zn^{++}\,S^{=}$$

$$Zn: + \ddot{S}: \longrightarrow Zn^{++}\left[:\ddot{S}:\right]^{=}$$

The equation for the reaction of sulfur and iron to form the compound iron sulfide is analogous to that of zinc and sulfur and should be attempted by the student.

The formation of covalent bonds is illustrated by the reaction of oxygen and hydrogen to form water and by the combustion of carbon. The combination of oxygen and hydrogen may be represented thus:

$$2\,H_2 + O_2 \longrightarrow 2\,H_2O + 136{,}000\ cal.$$

$$2\,H:H + :\ddot{O}::\ddot{O}: \longrightarrow 2\,H:\ddot{O}:H + 136{,}000\ cal.$$

The above equation denotes that two gram-molecules of hydrogen unite with one gram-molecule of oxygen to form two gram-molecules of water. A mixture of oxygen and hydrogen in the volume ratio of 2:1 can be made at room temperature without any noticeable reaction taking place. The mixture will remain inert unless it is heated or ignited by means of a flame or spark, when combination takes place with explosive violence. The explosion is due to the fact that the large amount of heat indicated in the equation above is liberated at once. The gaseous mixture is heated and expands with explosive effect. The flame or spark which initiates

the reaction activates a few molecules, which break into atoms. These atoms, which are ejected from molecules, bombard other molecules, dissociating them and thus accelerating the reaction. As the molecules of oxygen and hydrogen disrupt, combination of the resulting atoms takes place. In such combination two bonds are formed between hydrogen and oxygen; the oxygen atom contributes two electrons and each hydrogen atom one electron, thus forming the two covalent bonds. But since oxygen is more electronegative (holds electrons with greater force) than hydrogen, the bonding electrons are displaced closer to oxygen, and hence oxygen is considered as the oxidizing agent and hydrogen the reducing agent.

Another example of a reaction involving simple combination and formation of covalent bonds is the combustion of carbon to form carbon dioxide

$$\cdot\dot{C}\cdot \;+\; :\ddot{O}::\ddot{O}: \longrightarrow :\ddot{O}::C::\ddot{O}: \;+\; 96{,}500 \text{ cal.}$$

$$\underset{\text{reducing agent}}{C} \;+\; \underset{\text{oxidizing agent}}{O_2} \longrightarrow CO_2 \;+\; 96{,}500 \text{ cal.}$$

Though the electrons in carbon dioxide are shared, they are considered to be closer to oxygen atoms than to carbon atoms. Hence, the carbon in carbon dioxide is in the oxidized form and the oxygen in the reduced form. It will be noted that the amount of heat liberated for every gram-molecule of carbon dioxide formed is 96,500 calories. This forms the basis of the use of carbon compounds as fuels.

Replacement reactions are illustrated by the action of dilute hydrochloric acid on zinc. The zinc metal dissolves and hydrogen gas is evolved. The reaction is represented thus:

$$Zn: \;+\; 2\,H^+Cl^- \longrightarrow Zn^{++}\;\; Cl^-_2 \;+\; H_2$$

It is called simple replacement because the zinc metal replaced hydrogen in hydrochloric acid forming zinc chloride. An inspection, however, will show that this chemical change involves transfer of electrons; the metallic zinc on the left side of the equation has no charge, whereas on the right side it appears as a positive ion. Obviously, then, the zinc atom lost the electrons (acted as a reducing agent) and the hydrogen ion acquired the electrons (acted as an oxidizing agent):

$$Zn: \longrightarrow Zn^{++} \;+\; 2\,e$$

$$2\,H^+ \;+\; 2\,e \longrightarrow H{:}H \text{ or } H_2$$

These simple replacement reactions may be used to study the activity of metallic atoms, that is, the ease with which the metallic atoms react by losing or donating electrons. Consider an experiment in which small pieces of magnesium, calcium, and barium are dropped into water. Small bubbles of hydrogen gas appear slowly on the surface of magnesium; they form more readily in the case of calcium, and still faster in the case of barium

m. If more barium metal is added and the reaction is allowed to pro-ed, a precipitate of the sparingly soluble barium hydroxide appears:

$$\underset{\text{Barium}}{\text{Ba:}} + \underset{\text{Water}}{2\,H^+OH^-} \longrightarrow \underset{\text{Hydrogen}}{H:H} + \underset{\text{Barium hydroxide solution.}}{Ba^{++} + 2\,OH^-}$$

the equation shows, the reaction between the metal and water consists the transfer of electrons from the metallic atoms to the hydrogen ions in ter. The hydrogen ions, after they gain electrons, become bubbles of drogen gas. The reason for the greater reactivity of barium is its larger mic radius and hence the larger distance of the valence electrons from e nuclear charge which holds them. This is indicated below:

$$\begin{aligned} &\text{Mg: (2, 8, 2)} &&\longrightarrow Mg^{++} + 2\,e \\ &\text{Ca: (2, 8, 8, 2)} &&\longrightarrow Ca^{++} + 2\,e \\ &\text{Ba: (2, 8, 18, 18, 8, 2)} &&\longrightarrow Ba^{++} + 2\,e \end{aligned}$$

rium has a greater radius than calcium, and hence its valence electrons e attracted with a smaller force by the nucleus than are those of calcium. the non-metals, the reverse holds true, for, since activity means attrac-n of electrons, the smaller the radius, the greater the activity. There-e, fluorine is more active than chlorine or iodine, because it can attract d hold electrons with greater force. Moreover, since it gains but one ctron and oxygen gains two, it is reasonable to expect fluorine to be more ctive than oxygen. On the basis of experimental data, it is possible to nstruct an "activity series" of metals and non-metals and correlate it th their atomic structure. Table 43 shows the activity series of some portant metals and non-metals.

Once the activity series is constructed from experimental data, it may used to predict reactions. In the column at the left are the electron nors or reducing agents, caesium (Cs) being the most active and fluoride n (F^-) the least. In the column at the right the electron acceptors or idizing agents are listed, fluorine (F_2) being the most active and caesium n (Cs^+) the least active. Indeed, fluoride ion and caesium ion are so ex-emely inactive that special methods must be employed to take an elec-n from the former or to give an electron to the latter, and the compound esium fluoride, CsF, is very stable. The table is so arranged that a re-cing agent will give electrons to any oxidizing agent below it; an oxidiz-g agent will take electrons from any reducing agent above it. Thus zinc ll give electrons to copper ion, that is, displace copper from solutions of salts:

$$Zn: + Cu^{++} \longrightarrow Zn^{++} + Cu:$$

nile copper will not react with solutions of zinc salts:

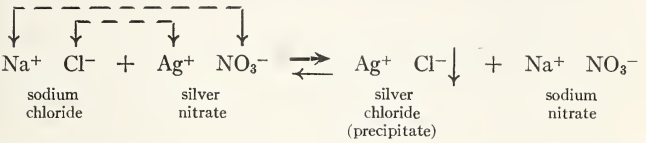
$$Cu + Zn^{++} \longrightarrow \text{no reaction}$$

TABLE 43. ACTIVITY SERIES OF SOME IMPORTANT METALS AND NON-METALS

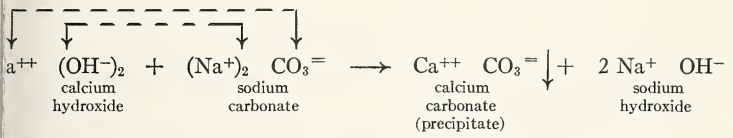
	Electron Donors	Oxidation, electrons lost	Electron Acceptors	
Active	Cs ·	⟶ ⟵	$Cs^+ + e$	Inactive
	Li ·	⟶ ⟵	$Li^+ + e$	
	Rb ·	⟶ ⟵	$Rb^+ + e$	
	K ·	⟶ ⟵	$K^+ + e$	
	Ba:	⟶ ⟵	$Ba^{++} + 2e$	
	Ca:	⟶ ⟵	$Ca^{++} + 2e$	
	Na ·	⟶ ⟵	$Na^+ + e$	
	Mg:	⟶ ⟵	$Mg^{++} + 2e$	
	Al:	⟶ ⟵	$Al^{+++} + 3e$	
	Mn:	⟶ ⟵	$Mn^{++} + 2e$	
	Zn:	⟶ ⟵	$Zn^{++} + 2e$	
	Cr:	⟶ ⟵	$Cr^{++} + 2e$	
Reductants	Fe:	⟶ ⟵	$Fe^{++} + 2e$	Oxidants
	Cd:	⟶ ⟵	$Cd^{++} + 2e$	
	Co:	⟶ ⟵	$Co^{++} + 2e$	
	Ni:	⟶ ⟵	$Ni^{++} + 2e$	
	Sn:	⟶ ⟵	$Sn^{++} + 2e$	
	Pb:	⟶ ⟵	$Pb^{++} + 2e$	
	H: H	⟶ ⟵	$2H^+ + 2e$	
	Bi⋮	⟵ ⟶	$Bi^{+++} + 3e$	
	As⋮	⟵ ⟶	$As^{+++} + 3e$	
	Cu:	⟵ ⟶	$Cu^{++} + 2e$	
	$2I^-$	⟵ ⟶	$I_2 + 2e$	
	Hg:	⟵ ⟶	$Hg^{++} + 2e$	
Inactive	Ag ·	⟵ ⟶	$Ag^+ + e$	Active
	$2Br^-$	⟵ ⟶	$Br_2 + 2e$	
	$2Cl^-$	⟵ ⟶	$Cl_2 + 2e$	
	Au ·	⟵ ⟶	$Au^+ + e$	
	$2F^-$	⟵ ⟶	$F_2 + 2e$	

The above statements are based on the assumption that the solutions volved are of a standard concentration.

2. *Partner exchanges.* When two substances such as sodium chloride d silver nitrate are mixed in the dry state, under ordinary conditions of nperature no visible chemical reaction occurs. If water is added, there a settling out or precipitation of silver chloride, and the reaction is repre-nted by the following equation:



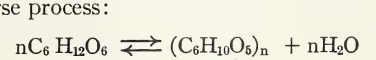
ne arrows indicate the ion exchange. Silver ions unite with the chloride ns to form silver chloride, which, owing to its small solubility in water, parates out. The sodium ions and nitrate ions remain in solution. If the ver chloride is removed by filtration and the filtrate is evaporated, then ystals of sodium nitrate are obtained. Another example of this type of emical reaction is the formation of precipitated chalk, or calcium car-nate:



ne calcium carbonate is not easily soluble in water and precipitates out, ving sodium and hydroxyl ions in solution.

3. *Complex reactions.* The explanations for complex reactions will not treated here because of their highly involved character. Generally, mplex reactions involve one or more of the following: (*a*) the union of nple molecules to form complex or larger molecules, (*b*) the disruption a large molecule to simpler molecules, (*c*) rearrangement of the atoms thin a complex molecule, thus giving rise to one or more different com-unds.

An example of the first type of complex reaction is the formation of a nthetic resin from the relatively simple gaseous hydrocarbon ethene, $_2H_4$ (Chapter 33), to yield solids whose molecular weights indicate the nion of 200 to 600 molecules to form new large aggregate molecules. nother example of the union of small molecules to form a more complex ne is the formation of starch from glucose which takes place in living atter. The preparation of glucose from starch which is done industrially ustrates the reverse process:



SUMMARY

1. Chemical reactions are classified into three groups: (*a*) reactions which i volve a transfer or shift of electrons; (*b*) reactions which involve exchange ions or partner exchanges; (*c*) complex reactions of organic compounds.
2. The chemical reactions which involve a transfer or shift of electrons a (*a*) simple combinations of elements to form ionic or electrovalent substanc (*b*) simple combination of elements to form covalent substances; (*c*) simp replacements.
3. The chemical reactions which involve transfer or shift of electrons are oft called *oxidation-reduction* reactions.
4. In simple combinations of elements the metallic atoms lose electrons or a as reducing agents; the non-metalic atoms gain electrons or act as oxidizi agents.
5. The more common metals and non-metals are arranged in a series of dimi ishing activity which can be related to their atomic structure.
6. In partner exchange reactions ions are exchanged without any actual transf of electrons from one atom or group of atoms to another.
7. Complex reactions of organic compounds involve one or more of the follo ing: (*a*) union of simple molecules to form larger; (*b*) disruption of larg molecules to simpler; (*c*) rearrangement of atoms within a complex molecul

STUDY EXERCISES

1. The following statements represent definite chemical changes. In the blan space preceding the item place:
   A if it is a reaction involving transfer or shift of electrons (oxidation-redu tion).
   B if it is partner exchange.
   C if it is a reaction other than A or B.
   .... (*a*) Copper when heated with sulfur turns black forming Cu_2S.
   .... (*b*) Hydrogen (H_2) passed over hot iron oxide (Fe_2O_3) forms Fe an H_2O.
   .... (*c*) When a sodium sulfate solution (Na_2SO_4) is added to a solution barium chloride ($BaCl_2$), a white solid, $BaSO_4$, settles out.
   .... (*d*) When magnesium carbonate is heated, magnesium oxide (MgC and carbon dioxide (CO_2) are formed.
   .... (*e*) Zinc when heated with sulfur forms ZnS.
   .... (*f*) Carbon monoxide (CO) when burned in the presence of oxyge forms CO_2.
   .... (*g*) When silver oxide (Ag_2O) is heated, it forms Ag and O_2.
2. Below is given a series of possible reactions. Insert:
   A if a reaction will take place
   B if no reaction is expected
   Use the activity series in this chapter as a guide in answering.
   (*a*) Zn: + H^+ ....
   (*b*) Fe: + Zn^{++} ....
   (*c*) Mg: + HCl ....
   (*d*) Hg: + Ag^+ ....

(*e*) $\dot{\dot{\text{Al}}}$ + Fe_2O_3 ....
(*f*) $\dot{\dot{\text{Al}}}$ + NaCl ....
(*g*) H^+ + Cu: ....
(*h*) Na· + HCl ....
(*i*) Na· + $AlCl_3$ ....
(*j*) $MgCl_2$ + Ca: ....
(*k*) Na· + HOH ....
(*l*) Zn: + H_2S ....
(*m*) Ca: + HBr ....
(*n*) Cl_2 + HI ....

. Briefly discuss how you would determine whether a compound which contains chlorine in combination with other elements is ionic or non-ionic.

. A chemical change involving oxidation-reduction is represented by each of the following equations. Complete each as shown in the first example.

R = reductant O = oxidant

$2\,Na + Cl_2 \longrightarrow 2\,NaCl$ $\qquad 2\,\underset{R}{Na\cdot} + \underset{O}{:\ddot{Cl}:\ddot{Cl}:} \longrightarrow 2\,Na^+ :\ddot{Cl}:^-$

Sodium + Chlorine ⟶ Sodium Chloride

(*a*) 2 Mg + O_2 ⟶ 2 MgO
(*b*) Zn + S ⟶ ZnS
(*c*) 2 Li + Br_2 ⟶ 2 LiBr
(*d*) Fe + 2 H Cl ⟶ $FeCl_2$ + H_2
(*e*) $Cu^{++}O^{=}$ + H_2 ⟶ Cu: + H_2O

. Using the activity series, select the right words in parentheses:

(Sodium ions, copper ions) have a greater tendency to gain electrons than have zinc ions.

(Tin, mercury) forms a more stable compound with oxygen than does copper.

(Silver, zinc) displaces copper from a solution of copper sulfate.

(Copper, silver) has a greater tendency to combine with oxygen than has mercury.

(Magnesium, zinc) displaces hydrogen ion more rapidly from dilute acids than does aluminum.

(Copper, iron) does not usually displace hydrogen ion from dilute acids.

(Potassium, magnesium) liberates hydrogen ion more rapidly from cold water than does calcium.

. The compounds HCl, HF, HI, HBr can be used to prepare the free halogens, Cl_2, F_2, I_2, Br_2. Instead of the hydrogen compounds, the alkali halides NaCl, NaF, NaI, and NaBr may be used with sulfuric acid. What type of agents must be used to obtain the free halogens? Arrange the halides according to increasing difficulty in undergoing such change.

. Use the activity series and supply the answers to the following questions by inserting in the blank space the letter which best completes the statement.

.... (*a*) The greatest tendency to lose electrons is exhibited by (A. silver; B. aluminum; C. copper; D. sodium).

.... (*b*) The lowest tendency to lose electrons is exhibited by (A. tin; B. gold; C. silver).

.... (*c*) The greatest tendency to gain electrons is exhibited by (A. chlorine; B. bromine; C. fluorine; D. iodine).

.... (*d*) The more stable compound with oxygen is formed by (A. tin; mercury; C. copper).

.... (*e*) Hydrogen ion is displaced from dilute acids more rapidly by (A magnesium; B. aluminum; C. zinc; D. mercury).

.... (*f*) The best coating for protection from corrosion is (A. tin; B. silve C. zinc; D. gold).

.... (*g*) Hydrogen ion is displaced from water more rapidly by (A. ma nesium; B. zinc; C. copper; D. calcium).

.... (*h*) The most unstable hydrogen compound of the elements of Grou VI is (A. H_2O; B. H_2Te; C. H_2S; D. H_2Se).

FOR FURTHER READING

1. Hatcher, W. H., *An Introduction to Chemical Science.*
Chapter 10 gives a discussion of oxidation and reduction.

2. Babor, J. A., *Basic College Chemistry.*
The activity of metals is discussed on page 87.

3. Briscoe, H. T., *College Chemistry.*
Oxidation-reduction is discussed on page 63, and the activity of metals pages 71–72.

31

A Study of Chemical Reactions II

THE PRECEDING CHAPTER the simpler types of chemical reactions were cussed. A number of questions will arise when the reader attempts to ply the principles given in that discussion to some of the daily experi- es of life. It is common knowledge that objects made of iron tarnish ily, whereas those made of chromium, silver, gold, and platinum tarnish ch more slowly. Most of us also know that the rate at which iron tar- hes under ordinary conditions of temperature is relatively slow as com- ed with that at higher temperatures. We have learned in Chapter 22 t certain oxidation changes of metals are called *rusting* when they occur wly, *combustion* when they take place rapidly. Still others, like the ning of gunpowder or of finely divided grain dust, are called *explosions*. o substances may be mixed with no visible change under one set of con- ions, but a marked change may occur when the conditions are changed. s important to know which reactions may be expected to take place eas- how to control those which proceed too violently, how to accelerate se that are slow, and how to change conditions so that reactions which not occur under ordinary circumstances may be made to take place. thout such knowledge modern industry would not be possible. The sent chapter will discuss briefly the factors which affect the velocities l the course of chemical reactions.

ilibrium

he most commonly held idea about a chemical reaction is that once it tarted it proceeds vigorously until the reactants are consumed. This ion is to some extent justified, for it is customary to illustrate the con- t of chemical change by the combustion of wood, the burning of mag- ium, or other simple reactions which take place within a period of a few nds. For example, after magnesium starts to burn, it proceeds vigor- ly until all the magnesium has changed to magnesium oxide; similarly,

when reacting quantities of zinc and sulfur are heated together, the rea tion does not stop until all the zinc and sulfur have combined:

$$\text{Zn} + \text{S} \longrightarrow \text{ZnS} + \text{Heat}$$
$$\text{Zinc} + \text{Sulfur} \longrightarrow \text{Zinc Sulfide}$$

However, most reactions which take place in nature do not proceed v rapidly and do not reach completion. Consider, for example, the reacti between carbon dioxide and water:

$$CO_2 + HOH \rightleftharpoons H_2CO_3 \qquad (1$$

Some of the carbon dioxide reacts with water to form carbonic acid, as m be demonstrated by taste or by addition of an indicator dye, such methyl orange, which turns to a pink color. The equation is written w reversed arrows to indicate that the reaction does not go to completion h is reversible. The product, carbonic acid, decomposes on warming to g carbon dioxide and water. The amount of carbon dioxide which rea depends on the solubility of carbon dioxide in water, which in turn depe on the temperature. If the beaker is cooled, more carbon dioxide dissolv For a particular temperature and pressure the amount of carbon diox which will dissolve in a given amount of water is definite. At 20° C. an pressure of one atmosphere, 0.12 gram of carbon dioxide dissolves in 1 milliliters of water. In such a solution there are two reactions tak place. One involves the formation of carbonic acid and is represented the arrow pointing to the right in equation (1); the other involves the composition of carbonic acid and is represented by the arrow pointing the left. Immediately after carbon dioxide begins to dissolve and re with water, the rate of formation of carbonic acid is rapid; but as the re tion proceeds and carbonic acid accumulates, the reverse reaction proce faster and faster. Finally, the two rates must become equal. When t condition is reached, new carbonic acid molecules are formed at the sa rate as other molecules of carbonic acid decompose to carbon dioxide a water. When this balanced condition is reached and the two oppos reactions proceed at equal rates, the system is said to have reached the c dition of *chemical equilibrium*. It should be noted that the condition equilibrium is not static but is dynamic, for there are reactions going on all times; but since the two opposing reactions go at equal rates so far as net result is concerned, the reaction may be considered apparently to ha ceased.

Another point that should be emphasized is that when a reaction reac equilibrium, it has not necessarily progressed halfway or fifty per c One reaction may proceed only five per cent and reach equilibrium, a another eighty per cent. What is more important is that the equilibri state of a reaction, or the extent to which the reaction proceeds be equilibrium is attained, depends on the conditions under which the react

akes place. If, for example, a beaker of water in which solid carbon ioxide dissolves is placed in an enclosed vessel under pressure, the amount f carbon dioxide which will dissolve and hence the amount of carbonic cid formed will be greater than under the conditions given above. Therefore, the equilibrium point of the reaction (1) will be different at different ressures.

The dynamic nature of equilibrium may be likened to a tug-of-war. If he muscular power of the freshman team and of the sophomore team are qual, neither team is able to move the other. But should an individual on ne side lose his foothold, the other side will have the advantage and be ble to move backward. Equilibrium is established again, however, when he losing team establishes another foothold.

This discussion indicates that, contrary to the first impression, many hemical reactions do not take place instantly nor proceed to completion. A large number of chemical reactions are *reversible* reactions. When the pposing reactions occur at the same speed, a condition of equilibrium is eached. Such reactions may be made to go either way, depending on the onditions. In the first place, the speed with which equilibrium is reached epends on the nature of the reacting substances, the temperature, the oncentration of the reacting substances, the state of their subdivision, and he catalysts used. In the second place, once a state of equilibrium is eached, it is often possible by changing the conditions — such as temperature, pressure, and concentration of the reacting substances — to displace he equilibrium by changing the speed of one of the reactions.

In considering whether a reaction will occur when two substances A and B are mixed and whether the reaction will take place slowly or rapidly, the ollowing generalizations can be made:

1. The type of reaction between A and B depends first on their nature, hat is, on their activity. If they are elements, their position in the Periodic Table and their electronic configuration will give information as to heir general chemical reactivity. This will indicate whether a reaction is ossible. Consider, for example, the reaction of chlorine with aluminum nd the reaction of chlorine with oxygen. Since aluminum is a metal and nder appropriate conditions can transfer electrons to chlorine, it can be redicted that they will react rapidly. Chlorine and oxygen, on the other and, both tend to act as electron acceptors. In this case it can be stated hat the elements will not react with each other with ease, and if they do eact the bond will be relatively unstable; hence the compound between xygen and chlorine will be unstable and therefore will have high activity.

2. The activity of an element, as indicated in the preceding paragraphs, an be deduced from the electronic configuration of the element and its osition in the Periodic Table. Generally the ionizing potential (refer to age 489) of gaseous atoms increases along each period beginning with an lkali metal and ending with a noble gas. This indicates that the elements

of Groups I and II tend to lose electrons readily while those of Groups V and VII tend to gain electrons. Further, within any particular grou electrons are lost with increasing ease as the atomic radius increases (s page 549). Experimental proof of this conclusion can be obtained readi in the laboratory.

The activity of the common metals and non-metals has been discussed Chapter 30. A few examples will illustrate how these principles apply the prediction of whether a reaction will take place and, if it does, wheth the speed will be slow or rapid.

Let it be assumed that lead oxide, $Pb^{++}\ O^{=}$, is to be reduced to metall lead. Stated in another manner, the lead ion, Pb^{++}, is to acquire two ele trons and become a metallic atom, Pb. In order to do so, it is necessary heat the lead oxide with a more active electron donor, or reducing agen than the Pb atom. Inspection of the table on activities (page 550) w disclose a number of common metals which are above the Pb, Pb^{++} pa and will therefore reduce the Pb^{++} ions in the lead oxide to metallic lea It is easy to verify experimentally that metals such as magnesium, alum num, zinc, or iron, when heated with lead oxide, produce metallic lead. for example, aluminum is used, the reaction can be represented as follow

$$2\ \overset{\cdots}{\mathrm{Al}} + 3\ Pb^{++}\ O^{=} \longrightarrow \overset{+++}{\mathrm{Al}}_2O^{=}_3 + 3\ Pb:$$

Assume now that separate experiments are made. In each lead oxide heated separately with: (*a*) potassium metal; (*b*) copper powder; (*c*) t powder. By inspection of the activity table it can be predicted that pota sium will react very rapidly, that copper will not react, and that with t the reaction will be very slow.

Effect of Temperature

The spectacular experiments in chemical changes performed for t benefit of the student often give a wrong impression as to the velocity chemical reactions. The burning of magnesium in air and of iron wire oxygen, or the instantaneous explosions of previously prepared mixtur may lead to the erroneous conclusion that chemical reactions have to "coaxed" until they start and that they are over in the twinkling of eye. Fortunately, this is not true, else life on earth would be very difficu The elements and compounds which react very rapidly do not occ free in nature; it is only through the contrivance of the scientist th they are prepared in order that they may be used to obtain specific result For example, chlorine is prepared in order to use it, among other applic tions, for the treatment of drinking water. Most chemical reactions pr ceed slowly; hence we are obliged to study all the possible methods which their velocities may be increased. But sometimes we may be inte ested in decreasing the velocity of the change. For example, the rubb of automobile tires undergoes oxidation and thereby becomes britt

Study of the oxidation changes of carbon compounds has led to the development of substances which decrease the rate of oxidation of rubber, and as a result the mileage of automobile tires has been increased.

From a scientific point of view, the ancient and honored art of cooking is based upon the principle that elevated temperatures increase the velocity of chemical changes. Meats and vegetables are partially predigested by cooking, and digestion involves a great many chemical changes. A five-pound roast can be cooked at 150° F. if the housewife is willing to wait twenty-four hours, but it is usually cooked at 350° F. in about two hours. In the same way mixtures are "cooked" in test tubes, flasks, and beakers in the laboratory or in the vats of chemical factories. The essential operations of most chemical factories are cooking, distilling, filtering, and drying.

We have seen that when a substance or a mixture of substances is heated, the kinetic energy of the molecules is increased. The molecules move faster, so collide more often. (They waste less time between collisions.) The more collisions, the more opportunities for reaction. Raising the temperature, therefore, should increase the speed of reactions. Also, heat increases the vibration of the atoms and electrons within the molecules, so that partial disruption may occur, leading frequently to the formation of ions. The formation of ions leads to reaction. The speed of most chemical reactions is doubled for every 10° C. increase in temperature.

A very simple demonstration of the effect of temperature is afforded by copper foil. It is known that copper tarnishes, or oxidizes, very slowly. If a piece of copper foil is held for five seconds over the tip of a gas flame, it tarnishes immediately, with the formation of black copper oxide:

$$\underset{\text{Copper}}{2\,Cu} + O_2 \rightleftarrows \underset{\text{Copper oxide}}{2\,CuO}$$

The oxidation of copper at ordinary temperature proceeds at a very slow rate and, further, the equilibrium point is reached after a small amount of copper and oxygen have reacted. When the temperature is increased, both the forward and reverse rates are increased and the equilibrium point is reached with greater speed.

Effect of Subdivision

If the reacting substances are in the solid state, the reaction proceeds slowly. To accelerate the speed of reaction, solids may be changed to the liquid or gaseous state by heating. In solids the motion of molecules or ions is mainly vibration within the boundaries of the crystal; hence, molecular or ionic collisions are not frequent. In the liquid, and particularly in the gaseous state, the motion of molecules is in all directions; as a result there are frequent collisions. More often, however, solids are dissolved in a medium which will produce molecular or ionic dispersions. In general, the finer the subdivision, the greater the speed; molecular or ionic sub-

division is attained in the liquid and gaseous states or in solutions. Sub division does not have any effect on the equilibrium point of a reversib reaction.

Catalysts

Many reactions in nature and in industry take place in the presence small amounts of other substances which apparently remain unchanged the process, although they increase or decrease the velocity of chemic changes. Such substances are called *catalysts*. A convenient experimen to illustrate the effect of a catalyst can be performed with very inexpensiv materials. A bottle of hydrogen peroxide may be obtained from any drug store. It consists of a three per cent solution of hydrogen peroxide (H_2O in water, and is used as an antiseptic. The hydrogen peroxide decompose slowly into water and atomic oxygen thus:

$$\underset{\text{Hydrogen peroxide}}{H_2O_2} \rightleftarrows \underset{\text{Water}}{H_2O} + \underset{\text{Oxygen}}{\ddot{O}:}$$

When it has stood for some time, a sealed bottle of hydrogen peroxid develops a slight pressure, evident when the cap is turned, because of i slow decomposition. The rate at which decomposition takes place — or th speed of the reaction to the right in the above equation — may be increase by the addition of an appropriate catalyst. A small amount of manganes dioxide (MnO_2) causes violent frothing. A lighted splinter placed abov the solution bursts into a brilliant flame, thus indicating a higher concen tration of oxygen than in air. The mere presence of a small amount of th black substance accelerates the speed of the decomposition; the manganes dioxide remains unchanged. A similar effect is produced when hydroge peroxide is placed upon a cut or in the mouth. Bubbles or a froth oxygen are formed; the oxygen is active, being in the atomic state, an hence it exerts antiseptic action. The catalysts in the tissues are produce by living matter and are called *enzymes*. Enzymatic catalysis is the bas of practically all chemical reactions in the living cells. The digestion food, the oxidation in the tissues by which energy required for life is pr duced, the building and the degradation of substances in the cells, a accomplished through reactions accelerated by enzymes. Consider, f example, what happens when we eat four ounces of meat: at a temperatu of 37° C. (98.6° F.) we digest it — or break it up into simpler molecules in two to three hours. To do the same thing in the laboratory it is nece sary to heat it at 100° C. (212° F.) with 25 per cent sulfuric acid for twent four hours. The body uses enzymatic catalysis.

It is also possible to find substances which retard the decomposition hydrogen peroxide. Thus commercial hydrogen peroxide contains a sma amount of a substance called *acetanilide* which inhibits the rate of decom position. Such substances are called *inhibitors*. Another example of a

nhibitor has already been mentioned. Rubber reacts with oxygen, form-ng compounds which reduce its elasticity; in rubber tires the reaction is ccelerated owing to the heat developed by friction. The tire ultimately ecomes prematurely aged. The addition of a small amount of an inhibitor /hich can combine with oxygen prolongs the life of the tire. Organic ompounds with reducing properties, such as diphenylamine and related ompounds, are used as rubber inhibitors, or *antioxidants.*

ffect of Concentration

A very important factor which influences not only the speed but also the quilibrium point of a reaction is the relative *concentration,* which may be efined as the amount of a reacting substance within a given volume. t is convenient to express concentration in terms of gram-molecules per ter. In order to illustrate the effect of concentration we will consider n experiment in which carbon dioxide reacts with a solution of calcium ydroxide. It was shown on page 556 that carbon dioxide reacts with /ater reversibly as follows:

$$CO_2 + H_2O \rightleftarrows H_2CO_3 \qquad (1)$$

f a lump of dry ice is dropped into a solution of calcium hydroxide, the olution becomes milky because solid calcium carbonate forms:

$$\underset{\text{Calcium hydroxide}}{Ca(OH)_2} + \underset{\text{Carbonic acid}}{H_2CO_3} \longrightarrow \underset{\text{Calcium carbonate}}{CaCO_3} + \underset{\text{Water}}{2\,H_2O} \qquad (2)$$

f the solution of calcium hydroxide is diluted by adding water, and only a inute amount of carbon dioxide is added, the solution does not become loudy immediately; the decrease in the concentration of the reacting sub-tances has decreased the rate of reaction. If the quantities of calcium ydroxide and water are kept at the same temperature, and the quantity f carbon dioxide is doubled (equation 2), first there will be an increase n the rate of reaction, as shown by the appearance of cloudiness in a horter period of time; but as the evolution of carbon dioxide proceeds, the loudiness of the solution disappears, because calcium carbonate reacts vith carbonic acid to form the soluble calcium bicarbonate. In order to how the relations, equations 1 and 2 are repeated here:

$$H_2O + CO_2 \rightleftarrows \underset{\text{Carbonic acid}}{H_2CO_3} \qquad (1)$$

$$H_2CO_3 + Ca(OH)_2 \rightleftarrows \underset{\text{Calcium carbonate}}{CaCO_3\ (\text{insoluble})} + 2\,H_2O \qquad (2)$$

$$CaCO_3 + H_2CO_3 \rightleftarrows \underset{\text{Calcium bicarbonate}}{Ca(HCO_3)_2\ (\text{soluble})} \qquad (3)$$

\fter the solution of the carbonate, if the quantity of carbonic acid is educed, the point of equilibrium will shift to the left, and calcium carbon-

ate will precipitate out. The shifting of the equilibrium state in the rea tions, represented by the three equations above, occurs in nature in th formation of stalactites and stalagmites. When carbon dioxide dissolves i rainwater as it falls to the ground, the reaction represented by equation takes place. When ground water percolates through a limestone bed calcium bicarbonate forms in accordance with equation 3. When groun water drops in a cave, the loss of carbon dioxide and evaporation of wate cause the equilibrium of reaction 3 to shift to the left, and crystallin calcium carbonate (calcite) precipitates to form the stalactites and stalag mites. (See page 148.)

Reactions Between Ions in Solution

In the preceding chapter under the discussion of the types of chemica change, the partner exchange type was briefly discussed as the simples chemical reaction. Such changes involve exchange of ions and take plac usually in water solutions of the compounds.

Solutions. Reactions in aqueous solutions are extremely important sinc the largest component of living tissues is water, and therefore most rea tions, if not all, taking place in living tissues are reactions of water solution

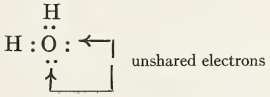
The components of a solution are often designated as the *solute* and th *solvent.* In preparing a solution of sugar or salt in water, the solid i designated as the *solute* and water as the *solvent.* In dissolving one liqui in another, as, for example, alcohol in water, the component present i greater proportion is called the solvent. However, the ambiguity of th terms solvent and solute, which occurs when the components are presen in approximately equal amounts, can be removed by stating that a solutio contains so much of each component.

One of the chief characteristics of solutions is that they are homogeneous that is, the composition (proportion of solute and solvent) and propertie are the same throughout; the dissolved material does not settle out eve if it has greater density than water. This indicates that the particles o solute are either molecular or ionic in size and are in constant motion, thu giving a uniform distribution throughout the solution. When the particle consist of an aggregate of many molecules, as is often the case in solution of substances which have high molecular weights (starches and proteins) they are called *colloidal solutions*, or better, *colloidal dispersions.* Thi implies that they are not true solutions but comparatively large aggregate of a solute dispersed between the molecules of the solvent. Such dispe sions when examined by a special type of microscope demonstrate th motion of particles, made apparent by the reflection and refraction o light by the large molecular aggregates. If these molecular aggregate grow by attraction of one particle to another, they ultimately becom visible and may form a *suspension* which may settle from the solutio slowly. Suspensions are usually formed by dispersing an extremely finel

vided solid in a solvent in which it is insoluble. For example, finely vided clay or silica when shaken with water forms suspensions. Such ixtures are not homogeneous and can be separated by filtration.

Solutions of Ionic and Polar Compounds. Brief mention of the ionization polar and ionic compounds in water solutions was made on page 541. was pointed out that ionic compounds such as sodium chloride, potassium romide, and the like, when dissolved in water separate completely into ositive and negative ions. On the other hand, polar compounds such as ydrogen chloride, ammonia, and acetic acid ionize to a variable degree hen they are dissolved in water. The degree of ionization depends on e nature of the atoms within the molecule or the displacement of the ectrons forming the chemical bonds. In the present section the mechan- n of solution of these types of compounds and some of their properties ll be treated in greater detail.

It was pointed out in Chapter 29 that water has a dipolar molecular ructure. When ionic compounds such as sodium chloride are placed in ater the dipolar water molecules orient themselves as shown in Figure 9, *b* (page 541). This orientation decreases the force of attraction tween the oppositely charged ions. At the same time the ions can attract e water dipoles and even form a weak combination with them through e two unshared pairs of electrons which each water molecule has on the ygen atom:



he process of solution of sodium chloride therefore consists first in the eakening of the electrostatic bonds between the oppositely charged ions d then in the association of the ion with an envelope or cluster of water oles. Thus the ions surrounded by water molecules, or hydrated, move rough the solution. The number of water dipoles associating with each n depends on its radius and its charge, and in many instances this number not known.

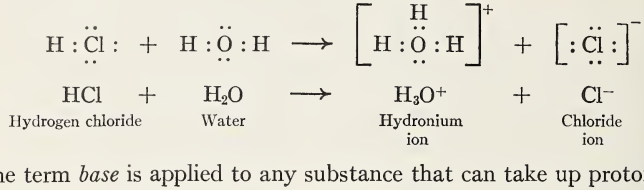
The solution of polar compounds in water follows the general rule that e dissolves like. Non-polar liquids such as hexane, C_6H_{14} (a constituent gasoline), dissolve with ease fats and oils which are mixtures of non-polar mpounds and are insoluble in water.

The molecules of polar compounds are asymmetrical, and in associating th water dipoles, chemical bonds which are already weak due to the equal attraction of strong and weak electronegative atoms are further eakened, and the molecules undergo ionization. The molecules or their ns often form bonds with water molecules, as will be illustrated in the xt section. The extent to which ionization takes place depends on the

compound and the bonds by which its atoms are united. Some compou dissolve with complete ionization while others ionize only to a very sli degree. Therefore a solution of a polar compound may contain both i and molecules of the solute.

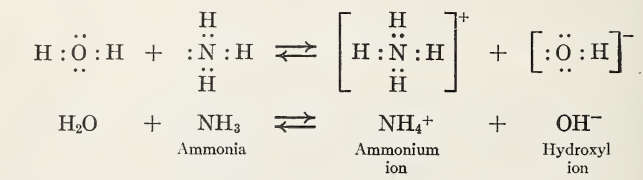
Strong and Weak Electrolytes. One of the most characteristic proper of solutions of ionic compounds and of polar compounds in water is t they conduct an electric current. They are therefore called *electroly* The three classes of electrolytes are: *acids*, *bases*, and *salts*.

The term *acid* has been traditionally known to denote a compou which in water solutions has a sour taste, changes the color of blue litm to red, and liberates hydrogen gas when it acts upon such active metals magnesium, zinc, aluminum, and the like. In the modern nomenclatu an acid is a substance that gives off a proton (hydrogen ion, H^+) in soluti The proton unites with water molecules to form a "hydronium" ion wh in the simplest form can be represented thus:



HCl	+	H_2O	⟶	H_3O^+	+	Cl^-
Hydrogen chloride		Water		Hydronium ion		Chloride ion

The term *base* is applied to any substance that can take up protons. I example, ammonia is a base, since it can accept a proton to form ammonium ion:



H_2O	+	NH_3	⇌	NH_4^+	+	OH^-
		Ammonia		Ammonium ion		Hydroxyl ion

It will be seen that the ammonium ion can decompose back to give a prot H^+, and the base ammonia, NH_3. Therefore the fundamental relations between an acid and a base can be formulated as follows:

$$\text{Acid} \rightleftharpoons \text{Base} + \text{Proton}$$

If equation (1) is again considered, the chloride ion is the base result from the transfer of a proton from the hydrogen chloride molecule to water molecule. However the water molecule in accepting a proton a as a base (proton acceptor). The net result is that the transfer of a pro from an acid to a base results in the formation of a new acid and a new ba

$Acid_1$	+	$Base_1$	⇌	$Acid_2$	+	$Base_2$
HCl	+	H_2O	⇌	H_3O^+	+	Cl^-
H_2O	+	NH_3	⇌	NH_4^+	+	OH^-
H_2SO_4	+	H_2O	⇌	H_3O^+	+	HSO_4^-

Note that in equation (4) water acts as a base and that in equation (5) it acts as an acid. Therefore water molecules can take protons from each other. This occurs to a very slight extent:

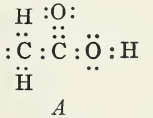
$$\underset{A_1}{H_2O} + \underset{B_1}{H_2O} \rightleftharpoons \underset{A_2}{H_3O^+} + \underset{B_2}{OH^-}$$

Hydronium ion — Hydroxyl ion

In neutral water the number of hydronium ions and hydroxyl ions is equal. Addition of an acid will increase the concentration of the hydronium ions and the solution will become acidic, while addition of a base will decrease the number of hydronium ions, and hence will increase the concentration of hydroxyl ions, and the solution will become alkaline.

The term *salt* has been met already many times. First it was applied to the compounds formed by a typical metal with a typical non-metal. More generally, the term was applied to substances which in the solid form have an *ionic lattice* and in water solution are appreciably dissociated into ions. A few compounds resulting from the union of a metal and non-metal are known, such as mercuric chloride, $HgCl_2$, which do not ionize appreciably in water solutions. Such compounds are regarded as covalent compounds.

Very active acids which in dilute solutions are completely ionized are classified together with the ionic salts and are called *strong electrolytes*. The most common acids, hydrochloric (HCl), nitric (HNO_3), and sulfuric (H_2SO_4) belong in this group. On the other hand, there are a large number of compounds which when dissolved in water are only slightly ionized and are called *weak electrolytes*. An example of a weak acid is a solution of acetic acid; white vinegar is approximately a 5 per cent solution of acetic acid. The formula of acetic acid may be written in a number of ways:



A

$HC_2H_3O_2$

B

Formula *A* depicts the structure, while formula *B* is an abbreviated or condensed formula of the compound. The structure in formula *A* indicates that of the four hydrogen atoms one is different in that it is attached by an intermediate bond to oxygen while the other three are attached by regular covalent bonds to a carbon atom. The oxygen-hydrogen bond is considered as an intermediate bond (between the covalent and the typical ionic), since the electrons are attracted closer to the oxygen than to the hydrogen, and hence it is possible for this hydrogen to be donated to water molecules when acetic acid is dissolved in water. By use of the abbreviated formula for acetic acid, the ionization can be written thus:

$$\underset{A_1}{HC_2H_3O_2} + \underset{B_1}{H_2O} \rightleftharpoons \underset{A_2}{H_3O^+} + \underset{B_2}{C_2H_3O_2^-}$$

Acetic acid — Acetate ion

The arrows denoting the equilibrium in the equation for the ionization of acetic acid indicate that the equilibrium point is considerably to the left and that water, H_2O, is a weaker base than the acetate ion, $C_2H_3O_2^-$, and hence only a few protons are accepted by the water. Conductivity measurements indicate that the degree of ionization remains below 5 per cent even when as little as one hundreth of a mole of acid (0.6 g) is dissolved in a liter of water. In general, the degree of ionization of a weak electrolyte increases with dilution.

As an example of a weak base, the solution of ammonia in water may be considered: the reaction is shown in equation (2), page 564. The reaction to the right depends on the ability of ammonia ($base_1$) to take protons from water molecules, while the reaction to the left depends on the ability of hydroxyl ions ($base_2$) to take protons from ammonium ions. In the competition for protons between the oxygen atom of the hydroxyl ion and the nitrogen atom of ammonia the attraction is greater in the former — or, as it is commonly expressed, the hydroxyl ion is a stronger base than ammonia — and hence the equilibrium state is considerably to the left and ammonia acts as weak base in water solutions.

Reactions Involving Exchange of Ions. The reactions which in the beginning of this chapter were called partner exchanges may now be considered in the light of the discussion on solutions.

(*a*) *Reaction of ions to form a weak acid or base* (*weak electrolyte*). If to a solution of sodium hydroxide a drop of an organic compound called phenolphthalein is added, a pink color develops. Phenolphthalein has this characteristic color in water solution if the concentration of hydroxyl ions is very slightly above that of the hydronium ions:

$$H_2O + H_2O \rightleftharpoons H_3O^+ + OH^-$$

When the concentration of the hydronium ions and hydroxyl ions become approximately equal, the pink color disappears. Hence phenolphthalein can be used as an indicator for neutrality. The sodium hydroxide solution is now mixed slowly with a dilute solution of hydrochloric acid, being stirred at each addition of acid. It is found that, as the acid is added dropwise, a point will be reached when one additional drop of acid discharges completely the color of phenolphthalein, indicating that the numbers of hydroxyl and hydronium ions are equal. This process is called *neutralization* of a base by an acid.

Solution $Na^+ + OH^- + H_3O^+ + Cl^- \longrightarrow Na^+ + Cl^- + 2\,H_2O$

(Sodium hydroxide; Hydrochloric acid)

or simply $OH^- + H_3O^+ \rightleftharpoons H_2O + H_2O$

(Hydroxyl ion; Hydronium ion)

The neutralization of the base is essentially the reaction between two ions to form a slightly ionized molecule or weak electrolyte. This force shifts

e equilibrium to the right: the hydroxyl and hydronium ions combine form molecular water.

Another example of the same type of reaction is the addition of a latively strong acid to a solution of sodium carbonate. Consider, for ample, the addition of dilute sulfuric or hydrochloric acid to a solution sodium carbonate. As the acid is added considerable effervescence curs with evolution of carbon dioxide. The reaction may be represented follows:

$$Na_2CO_3 + 2\,HCl \longrightarrow 2\,Na^+Cl^- + H_2O + CO_2$$

$$\begin{array}{lllll} \text{Reactions} & H_3O^+ + CO_3^= & \rightleftharpoons & H_2O + & HCO_3^- \\ \text{of ions} & H_3O^+ + HCO_3^- & \rightleftharpoons & H_2CO_3 + & H_2O \\ & & & \downarrow\uparrow & \\ & & & CO_2 + & H_2O \end{array}$$

he equations show that the reactions of ions produce the slightly ionized rbonic acid which is unstable and decomposes into carbon dioxide and ater (page 556).

(*b*) *Reaction of ions to form precipitates.* The reaction of silver nitrate th sodium chloride (page 551) may be written in the following manner:

$$Ag^+ + Cl^- \rightleftharpoons AgCl \downarrow \text{ Solid}$$

reactions of this type the precipitate forms if the concentration of the ns in the solution exceeds a certain value. The discussion of this type equilibrium is beyond the scope of this text; suffice it to state that the rmation of precipitates by the reactions of ions in solution is governed two factors: (1) the solubility of the particular precipitate in water,) the concentrations of ions which are present in each particular case.

SUMMARY

. Under ordinary conditions most reactions reach an equilibrium at which there is a balanced activity between reactants and products.

. The extent to which a reaction proceeds before equilibrium is reached is known as the state of equilibrium.

. Increase in concentration, temperature, fine subdivision, and presence of catalysts increase the rate at which equilibrium is reached.

. Temperature and concentration may be varied so as to change the state of equilibrium, which is equivalent to changing the direction of the reaction.

. Solutions of ionic and polar compounds in water conduct an electric current and are called electrolytes. The three classes of electrolytes are acids, bases, and salts.

. Acids donate protons (hydrogen ions); bases accept protons.

. The reaction of an acid with a base is called neutralization; in aqueous

solutions, it is commonly the reaction between the hydronium and hydrox ions to form a weak electrolyte — water.

8. Ions react to form an insoluble precipitate if the concentration of the io in solution exceeds a certain value, which depends on the solubility of t compound which may precipitate out of the solution.

STUDY EXERCISES

1. Explain why chemical reactions of most inorganic compounds in the molt state or in solution take place more readily than in the solid state.
2. In the following exercises select the best completion of the statement:
   (*a*) The best explanation for the conductivity of electric current by an ion compound such as a solution of sodium chloride is: A. sodium is a metal element; B. some of the electrons are detached from the compound a conduct the current; C. Sodium is high in the electromotive series; Sodium chloride in water is ionized.
   (*b*) A catalyst is a substance that: A. affects the equilibrium; B. a substan which is used in the synthesis of ammonia; C. a substance which alt the speed at which equilibrium is reached; D. always increases the yi of the reaction.
   (*c*) Equilibrium is: A. a condition no chemical reaction reaches; B. a meth for activation of molecules in order that they may unite; C. the midpo of every chemical reaction; D. a condition in which two opposing re tions are taking place at equal velocities so that the concentration of t reacting substances remain constant.
   (*d*) The speed of a chemical reaction may be accelerated by: A. coolin B. pressure; C. use of an appropriate catalyst; D. dilution with an in solvent.
   (*e*) Neutralization refers to: A. reaction between an acid and water; B. so tion of a metal in an acid; C. reaction between an acid and a base; D. action between the oxide of a metal with water.
   (*f*) Electrolysis refers to: A. the reaction of elements in presence of an el tric current; B. the reaction between salt and water; C. the decompo tion of an electrolyte by the passage of an electric current through it.
   (*g*) In a reversible reaction at equilibrium:

$$NaNO_3 + H_2SO_4 \rightleftarrows NaHSO_4 + HNO_3$$

   A. doubling the concentration of sulfuric acid will drive the reaction le ward; B. removal of nitric acid will shift the equilibrium point to t right; C. removal of nitric acid will drive the reaction to the left; D. ad tion of more nitrate will diminish the speed.
3. After each of the following place the letter A if the solution is acidic, B if i basic, and N if it is neutral:

(*a*) solution of HCl in dry benzene .... (*c*) solution of glucose in water ..

(*b*) solution of HCl in water .... (*d*) solution of calcium oxide in wa

....

(*e*) solution of carbon dioxide in water ....
(*f*) solution of ammonia in dry ether ....
(*g*) solution of ammonia in water ....
(*h*) solution of alcohol in water ....

4. A dilute solution of sulfuric acid in water is mixed with a solution of calcium oxide in water. Complete the following equations which represent the reactions that take place:

(*a*) sulfuric acid + calcium hydroxide $\longrightarrow$ Calcium sulfate + ... (precipitate)
(*b*) $2\ H_3O^+\ SO_4^{--} + Ca^{++} + 2\ OH^- \longrightarrow Ca^{++}\ SO_4^{--} + \ldots.$
(*c*) $H_3O^+ + H_3O^+ \longrightarrow \ldots\ldots\ldots$
(*d*) $Ca^{++} + \ldots\ldots\ldots \longrightarrow Ca^{++}\ SO_4^{--}$

5. The following is a list of compounds. Mark with *A* if the compounds in aqueous solution have acidic properties; *B* if they have basic properties; *N* if they are neutral.

.... Oxides of metals.
.... Oxides of non-metals.
.... Hydrogen compounds of the halogens.
.... Hydrogen compounds of the oxygen family.
.... Hydrogen compound of N_2.
.... Halides of Group I and II.
.... Oxides of Group I and II.
.... Oxides of N and P.

6. List a number of applications of catalysts in everyday life.

7. Hydrogen passed into corn oil at 100° C. has no effect, but if a small amount of specially prepared nickel is present, the oil changes and becomes thick; and it is evident that hydrogen is absorbed in some way. Suggest some probable way by which nickel acts in such a change. The nickel at the end of the reaction is chemically unaltered.

8. Using the activity series, place before the symbol of the metal (1) if the substance listed will react with hydrochloric acid, and (0) if it will not react. In case of (1), give the formula of the product on the line after it:

.... Cu .... Ag .....
.... Mg .... Fe .....
.... K .... Au .....

9. Write the equations for the reactions that occur in the following aqueous solutions. In each case sufficient of each base is added until the color of phenolphthalen just changes to pink.

Sulfuric acid and sodium hydroxide:.....
Hydrochloric acid and calcium hydroxide:.....
Acetic acid and ammonia:.....

FOR FURTHER READING

1. Hatcher, W. H., *An Introduction to Chemical Science.*
Chapters 19 and 20 contain a discussion of equilibrium and solutions.

2. Hildebrand, J. H., *Principles of Chemistry.*
   A discussion on the speed of chemical reactions and chemical equilibrium w be found in Chapters 11, 12, 13, and 14.
3. Strong, R. K., *Chemistry for the Executive.*
   Chapter 3 gives a discussion of acids and bases. A discussion of solutio will be found in Chapter 6.
4. Babor, J. A., *Basic College Chemistry.*
   The speed of chemical reactions is discussed on page 228, solutions on pa 246, and electrolytes on page 260.
5. Briscoe, H. T., *College Chemistry.*
   The speed of chemical reactions is discussed on page 333, chemical equi brium on page 322, and electrolytes on page 121.

32

A Study of the Elements

IT HAS BEEN SHOWN that the atoms of the ninety-six known elements are all composed of the same fundamental particles, and that the chemical and physical properties of the elements are closely related to their atomic structures. The elements have been arranged in periods, groups, and subgroups, in accordance with the great generalization known as the periodic law, and within the periods and groups there is a gradual variation in properties from element to element. The close resemblance of the elements of a given group to each other, together with the gradation in properties, simplifies their study and even permits the prediction of the chemical and physical properties of an element from its position in the periodic table.

The various types of chemical change, the accompanying electronic changes, if any, and the factors affecting reaction velocities have also been considered, as well as the several classes of inorganic compounds which result from a chemical combination of two or more elements. Most of the principles underlying chemical properties and chemical changes were developed by people who were primarily motivated by the desire to know, to satisfy their intellectual curiosity, rather than by the intent to create something of practical value. Yet the application of theoretical principles, sometimes long after their formulation, inevitably leads to utility.

On the basis of the above principles, a few of the chemical elements and some of their compounds are considered in this chapter; the next chapter is confined to a study of the element carbon and some of its many compounds.

The chemical elements were conveniently classified in Chapter 29 under three types: inert gases, non-metals, and metals. The distinction between the latter two types is not always sharp, for, as might be expected from the periodic gradation in structure and properties, there are some elements which have properties of both metals and non-metals.

THE INERT GASES

The inert or noble gases — helium, neon, argon, krypton, xenon, and radon — compose Group 0 of the periodic system. Because the elements

are rather rare, chemically inert, and do not form compounds, they we not discovered until near the end of the last century. The first indicatio of the existence of such substances on this planet, however, was recorde by Henry Cavendish in 1785. Cavendish, who discovered hydrogen, firs determined the composition of water, and conducted experiments on th atmosphere, found that nitrogen could be removed from the air by oxida tion in an electric spark discharge. The acid oxide of nitrogen was remove by a base, the surplus oxygen which had been added was removed by com bustion, but a small inactive residue which "stood its ground" and whic "was not more than 1/120 of the whole" remained. This recorded fac stimulated no further investigation at the time, and remained unnotice for about a hundred years.

In 1868 J. Janssen, a French astronomer, observed in the spectrum of th sun's chromosphere, during an eclipse, a yellow line which did not corr spond to the spectrum of any known element. It was concluded by J. N Lockyer and E. Frankland that the yellow line was due to a new elemen which Lockyer named *helium* (*helios*, sun). Twenty-six years after Jans sen's observation, terrestrial helium was discovered by Sir William Ram sey, who obtained it by heating cleveite and similar minerals.

Shortly before the discovery of terrestrial helium, Lord Rayleigh ob served that the density of nitrogen obtained from the atmosphere by the re moval of the other known components was 1.2572 grams per liter, while tha of nitrogen obtained by the decomposition of its compounds was 1.250 grams per liter. This difference together with the certainty that all impur ties had been removed from the latter sample led to the inference that th nitrogen obtained from the air contains another gas of higher density tha nitrogen. The clue found by Cavendish over a hundred years before, no took on real significance. To test this hypothesis, Ramsay, who collabo rated with Rayleigh, carefully removed all the known gases from the air an obtained a gaseous residue (about one per cent of the air by volume) wit an atomic weight of 39.9. This he named *argon* (*argos*, idle, lazy) becaus of its chemical inertness. In the next few years Ramsay found helium i the atmosphere, and by fractional distillation of air obtained two ne gaseous elements with atomic weights of 82.9 and 130.2, which he name *krypton* (hidden) and *xenon* (strange), respectively.

Since the new inert elements did not fit into any of the groups of th periodic table proposed by Mendeleef, a new group (zero) was adde However, within this group, between helium and argon, there was a blan which indicated a missing inert element of atomic weight about 20. Th element was found in the atmosphere by Ramsay and named *neon* (ne one). The last element of the zero group, radon, produced by the radi active decay of radium and itself radioactive, was discovered by Ruthe ford.

Electronic Structure and Properties of the Inert Gases

In Chapter 29 the electronic structure of the inert gases was tabulated and attention was called to the unique stability of their atoms. Their high ionization potentials and chemical inertness offer experimental confirmation for the assumption that there is a symmetrically compact and generally stable arrangement of electrons in the various energy levels of the inert gases. Since the inert gases are in Group 0, they bridge the gap between the strongly electropositive elements of Group I and the strongly electronegative elements of Group VII. There are two electrons in the outer (K) orbit of helium, and eight electrons in the outer orbits of all the others. It was also shown, and is indicated later in this chapter, that atoms of many other elements gain or lose electrons in chemical changes, and that some of them acquire the configuration of the nearest inert gas.

Because of their stable electronic configurations, the inert gases do not gain or lose electrons, and can thus form compounds only by donating an electron pair to form a link with another atom. There is some evidence that such a union is effected between argon and boron trifluoride, ABF_3, but the compound is very unstable. Argon, krypton, and xenon also form crystalline hydrates with water under pressure.

The physical properties of the inert gases are shown in Table 44. Because of the complete electronic structure of the atoms, molecules of the noble gases are monatomic, that is, contain only one atom.

Table 44. The Inert Gases

Gas	Molecular Formula	Atomic Number	Electron Configuration	Density, grams per liter, S.C.	Boiling Point, °C.	Melting Point, °C.
Helium	He	2	2	0.1785	−268.9	−272.2
Neon	Ne	10	2, 8	0.9002	−245.92	−248.52
Argon	A	18	2, 8, 8	1.7836	−185.85	−189.52
Krypton	Kr	36	2, 8, 18, 8	3.743	−152.9	−156.6
Xenon	Xe	54	2, 8, 18, 18, 8	5.896	−107.1	−111.5
Radon	Rd	86	2, 8, 18, 32, 18, 8	9.97	− 62.	− 71.

Industrial Uses

Helium, which occurs in the natural gases in the Texas panhandle, in Kansas, and in Oklahoma, is produced and distributed by the United States Government. It is used in lighter-than-air craft, and mixed with oxygen it is employed in the treatment of certain respiratory diseases and in deep-sea diving. Other than the use of argon in the incandescent lamp (to prevent evaporation of the filament), the principal use of the other inert gases is in electric signs.

THE NON-METALS

General Properties

Non-metals are those elements, other than the noble gases, which do not

have metallic properties. That is, they are usually non-conductors of heat and electricity, they are brittle (if solid), and they lack the other physical properties such as tensile strength, malleability, etc., which characterize metals. In general, they are oxidizing agents, gaining electrons to form negative ions. Their oxides are acidic, combining with water to form oxy-acids; sulfuric acid (H_2SO_4) is an example. A number of non-metals combine with hydrogen to form compounds which are acids in water solution, as hydrogen chloride (HCl).

Although fewer in number than the metals, the non-metals constitute the greater portion of the earth's outer crust, and are widely distributed either in elementary form or in compounds. About 50 per cent of the earth's crust is oxygen, which occurs combined in the rocks and in water but is chemically free in the atmosphere. Silicon, the second most abundant element, constitutes about one-fourth of the earth's crust by weight.

Electronic Structure

The non-metals are found in the upper right-hand portion of the periodic chart, as is shown (together with atomic numbers and electronic structure) in Table 45 *a*.

Table 45 *a*. The Non-Metals

Group III	Group IV	Group V	Group VI	Group VII
$_5$B 2, 3	$_6$C 2, 4	$_7$N 2, 5	$_8$O 2, 6	$_9$F 2, 7
	$_{14}$Si 2, 8, 4	$_{15}$P 2, 8, 5	$_{16}$S 2, 8, 6	$_{17}$Cl 2, 8, 7
		$_{33}$As 2, 8, 18, 5	$_{34}$Se 2, 8, 18, 6	$_{35}$Br 2, 8, 18, 7
			$_{52}$Te 2, 8, 18, 18, 6	$_{53}$I 2, 8, 18, 18, 7

Molecules of the non-metals contain more than one atom. Two or more atoms, by sharing two (sometimes four) electrons, assume molecular configurations wherein each atom is surrounded by eight electrons, as shown

Table 45 *b*. Molecules of Some Non-Metals

	Fluorine	Hydrogen	Phosphorus	Sulfur
Simple molecular formula	F_2	H_2	P_4	S_8
Electronic formula of atom	:F·	H·	:P:	:S:
Electronic formula of molecule	:F:F:	H:H	P:P P:P	

Table 45 *b*. The structure of carbon in the form of diamond is three-mensional, and will be discussed in the next chapter.

The non-metallic properties decrease from top to bottom in a main group the periodic system, and in a period increase from left to right. Thus ›ron is the only non-metal in Group III, carbon and silicon are the only ›n-metals in Group IV, while all the elements of Group VII listed in ıble 45 *a* are non-metals. The most active non-metals are in Group VII, d the most active non-metallic element is fluorine. The elements in a ven group are similar in properties and valence, for they have the same mber of electrons in the outermost energy level.

›mpounds

The non-metals combine with hydrogen to form common and important mpounds, all of which are covalent, and either gases or volatile liquids. me of the hydrogen compounds, particularly those of group VII, are

Table 46. Hydrogen Compounds

III	IV	V	VI	VII
B_2H_6 diborane	CH_4 methane	NH_3 ammonia	H_2O water	HF hydrogen fluoride
	SiH_4 monosilane	PH_3 phosphine	H_2S hydrogen sulfide	HCl hydrogen chloride
		AsH_3 arsine	H_2Se hydrogen selenide	HBr hydrogen bromide
		SbH_3 stibine	H_2Te hydrogen telluride	HI hydrogen iodide

dic in water solution. In all the above compounds, except diborane, ch non-metal achieves, by sharing electron pairs, the electronic structure the inert gas following it. Nitrogen, for example, has the electronic ucture 2, 5. In ammonia the structure is:

d the combined nitrogen has an outer electronic structure of eight elec-ns, or 2, 8, which is that of neon.

The characteristics of acids and their common reactions were discussed the preceding chapter. A few of the important acids, all of which con-n non-metals, are listed in Table 47. It should be noted that the acids ich contain more than one ionizable hydrogen ionize in stages, the per-

centage of ionization being greatest in the first stage and progressive smaller for successive stages.

TABLE 47. COMMON ACIDS

Non-Metal	Acid	Molecular Formula	Ions formed in water solution
Boron	Boric	H_3BO_3	H_3O^+, $H_2BO_3^-$
Carbon	Carbonic	H_2CO_3	H_3O^+, HCO_3^-, $CO_3^=$
Nitrogen	Nitric	HNO_3	H_3O^+, NO_3^-
Sulfur	Sulfuric	H_2SO_4	H_3O^+, HSO_4^-, $SO_4^=$
Chlorine	Chloric	$HClO_3$	H_3O^+, ClO_3^-
Chlorine	Hydrochloric	HCl	H_3O^+, Cl^-
Phosphorus	Phosphoric	H_3PO_4	H_3O^+, $H_2PO_4^-$, $HPO_4^=$, PO_4

Uses

The element boron has very few industrial uses; boric acid, H_3BO_3, used as a mild antiseptic, and borax, $Na_2B_4O_7 \cdot {}_{10}H_2O$, as a water soften Little use is made of the free element silicon. However, the wide distrib tion and variety of silicon compounds in the earth's crust has been d cussed, and their uses in ceramics and building materials are well know Nitrogen and phosphorus are essential to life, nitrogen being a constitue of proteins, and calcium phosphate the chief component of the bones animals. Nitrogen, which is chemically rather inactive, forms compoun some of which are highly unstable and which are used as explosives. Le azide (Pb_3N_2) and trinitrotoluene ($C_6H_2(NO_2)_3CH_3$) are examples of su compounds. Sulfur, which occurs free, and also combined in sulfides, a in some proteins, is of considerable industrial use, particularly in the mar facture of sulfuric acid, which is probably the most important of the ind trial chemicals.

The halogens occur as salts, and from these salts the elements and large number of compounds are prepared. Chlorine, for example, is p pared from sodium chloride (table salt), and is used in the purification drinking water and in the manufacture of numerous industrial compoun This element forms a whole series of acids and salts; chlorides, hypoch rites, chlorites, chlorates and perchlorates, and numerous organic deri tives. Bromine and iodine form comparable compounds.

Hydrogen is unique in that its atoms react in several different ways: loss of electrons they form positive ions; by gain of electrons under suita conditions they form negative ions; and by sharing electrons they fo many covalent compounds. Indeed, hydrogen forms more compou than any other element.

THE METALS

One of the characteristics of our civilization is its dependence upon a multitude of machines — tools which are employed to alter the conditions imposed upon man by his natural environment. These machines, devices or the transformation of energy, are largely made of metals, the extensive use of which dates back over a period of only about 5000 years. Prior to this, tools were made of stone; hence the period known as the *Stone Age.* The first metals to be discovered and used were those which are found in the uncombined or chemically free state, that is, the less active metals — gold, silver, and copper. Native copper was probably the first metal to be used widely; admixed with tin it forms an alloy known as bronze. Both copper and bronze tools were common five thousand years ago. It is quite probable that the first iron used was of meteoric origin, for ability to separate iron and other metals from compounds found in the earth's crust (ores) was not achieved until about a thousand years before the Christian era.

Electronic Structure and Properties of Metals

The metals compose the main groups on the left-hand side of the Periodic Table, the heavier elements of the other main groups, and all of the sub-groups. Metals are the electropositive elements, for they lose their valence electrons more or less readily, functioning as reducing agents and forming independent positive ions. The most active of the metals, that is, the strongest reducing agents, are the members of Group I A, whose atoms have only one valence electron. Those of Group II A are next in chemical activity, each atom losing two electrons to form its ions. The ions of these two groups (see Table 48) have the electronic structure of the preceding inert gas. In each main group the tendency to lose electrons increases from top to bottom as the atomic radii increase, the most active of all metals being francium (Fr), which is at the bottom of Group I A. The high activity of the metals of these two groups explains why these elements are never found in the free state, and why their ions are very stable and difficult to reduce to the metallic state. The importance of these elements, other than beryllium and magnesium, which are used in the metallic state, lies in their compounds. Four of the six most important industrial chemicals are sodium compounds: sodium chloride, sodium carbonate, sodium hydroxide, and sodium silicate.

The oxides and hydroxides of the metals are generally bases (see Chapter 9), the strongest of which are those of the members of the two groups mentioned above. Nearly all the metal hydroxides, except those of Groups I A and II A, are insoluble in water and show their basic properties only by reacting with solutions of acids to form salts.

The activities of the metals, in general, decrease from left to right in the Periodic arrangement as the number of valence electrons increase. The

Table 48. Electronic Structure of Metals

Metal	Symbol and Atomic Number	Electronic Configuration	Ion	Electronic Configuration of Ion
Sodium	$_{11}$Na	2, 8, 1	Na^{+}	2, 8
Potassium	$_{19}$K	2, 8, 8, 1	K^{+}	2, 8, 8
Beryllium	$_{4}$Be	2, 2	Be^{++}	2
Magnesium	$_{12}$Mg	2, 8, 2	Mg^{++}	2, 8
Barium	$_{56}$Ba	2, 8, 18, 18, 8, 2	Ba^{++}	2, 8, 18, 18,
Aluminum	$_{13}$Al	2, 8, 3	Al^{+++}	2, 8
Tin	$_{50}$Sn	2, 8, 18, 18, 4	Sn^{++++}	2, 8, 18, 18
Iron	$_{26}$Fe	2, 8, 14, 2	Fe^{++}	2, 8, 14
Iron	$_{26}$Fe	2, 8, 14, 2	Fe^{+++}	2, 8, 13

electronic structures of some of the common metals and their ions a shown in Table 48. It should be noted that not all the metal ions have t inert gas structure; many have in their outer orbits some number of ele trons other than eight or two.

The characteristic physical properties of metals which can serve to di tinguish them from non-metals and upon which their uses depend a these: high density, ductility, malleability, tensile strength, thermal an electrical conductivity, hardness, and metallic luster. The properties a shown by the various metals in different degrees, and any particular pro erty may vary over a wide range. However, for most metals many of the properties are exhibited to a high degree.

Solid metals are crystalline, as shown by X-ray crystal analysis, an many of the physical properties are dependent upon the type of crystal la tice or arrangement of the atoms, the atomic radius, electronic structur and so on. An adequate treatment of this subject cannot be undertaken i this text, and only a few qualitative facts and ideas are mentioned. Th atoms arrange themselves in such a way that in most metals each atom in contact with either eight or twelve neighboring atoms. Because mo metal atoms have a small number of outer valence electrons (one or two there are not enough electrons to establish covalent bonds between eac atom and the adjacent atoms, such as exist in crystalline carbon. A met may be therefore regarded as an arrangement of positive ions in a cloud electrons. The attraction of the ions and the electrons for each other hol the ions together. Since the electrons are rather loosely held, and are n permanently attached to any particular ion, they move freely through th metal. The ions, which are not linked to each other by specific covale bonds, move relatively to each other when placed under a stress. Sever of the physical properties of metals, such as electrical conductivity an malleability, may be explained (see below) on the basis of this concept.

Density is the mass per unit of volume, and is usually expressed in gran per milliliter. The density of a solid element depends not only on the ma

of its atoms, but upon the number of atoms in a given volume. This is influenced by the electronic structure. In the atoms of the members of Group VIII, for example, there is an unusually compact electronic arrangement, and consequently low atomic volumes (the volume occupied by a gram atomic weight of a solid element). In this group the denser elements are found: platinum has a density of 21.45 g per ml; iridium, 22.4 g per ml, and osmium, 22.48 g per ml. On the other hand, the densities of magnesium and aluminum, both metals of considerable strength, are 1.74 g per ml and 2.7 g per ml respectively; hence these metals are used in airplane construction where a low density is of vital importance.

Ductility is the property which permits a substance to be drawn into very fine wires. Platinum, for example, may be drawn into wires 1/200,000 cm in diameter, wires which are invisible to the eye.

Malleability, the property which permits a substance to be rolled into thin sheets, is closely related to ductility. Many of the transition elements are both very ductile and malleable, especially those in Groups I B and VIII. Gold has been hammered into sheets 1/38,000 cm in thickness. When the metal is drawn or rolled the ions or kernels may be displaced with respect to their neighbors without destroying the binding forces of attraction between them and the electrons.

Tensile strength is the force required to break a rod or bar of the metal by a straight pull. Iron alloyed with vanadium, chromium, molybdium, wolfram (tungsten), nickel, or manganese forms steels of high tensile strength. This property is closely related to ductility, for it would be impossible to draw a very fine thread of a substance which does not have a high tensile strength.

Thermal and electrical conductivity, perhaps the most distinctive properties of metals, may be explained by the fast-moving free or mobile electrons. These electrons transmit heat energy from the hot portion of a metal to the ions in the cooler portion. Likewise, when the metal is connected in an electric circuit, the mobile electrons move faster in the direction of the electric field and their drift through the metal constitutes the electric current. The elements of Group I B, copper, silver, and gold, are all especially good conductors of both heat and electricity. Because of its high conductivity and lower cost, copper is extensively used in electric lines, radiators, and heating coils.

Hardness of metals is usually measured by the depth of the depression or indentation made by a steel ball under a given load for a given period of time. It is a desirable property in cutting steels and lathe tools. Of the elementary metals (not alloys), manganese is the hardest, while the metals of Group I B are very soft.

Other characteristics of metals which are factors in the determination of their uses are melting points and ability to resist corrosion. The transition metals of low melting points (all under 425° C.) are those in Groups I B,

II B, and germanium, tin, and lead in Group IV A. A number of low-melting alloys made from tin, lead, cadmium, and bismuth are of commercial use in fire alarm systems, automatic sprinklers, and fuses for electric circuits. One of these, Wood's metal, melts at 60° C. Metals of very high melting points are found in Groups V B, VI B, VII B, and VIII, especially those of higher atomic numbers in each group. Wolfram (tungsten), for example, has a melting point of 3370° C., and this property, together with its ductility, permits its use as an incandescent lamp filament.

Some of the properties of the common metals are shown in Table 49.

TABLE 49. PROPERTIES OF SOME METALS

Metal	Density,* grams per ml	Melting Point, °C.	Boiling Point, °C.
Aluminum	2.70	660	1800
Beryllium	1.80	1350	1500†
Chromium	6.9	1615	2200
Copper	8.92	1083	2300
Gold	19.3	1063	2600
Iron	7.86	1535	3000
Lead	11.34	327.5	1620
Magnesium	1.74	651	1110
Mercury	13.55	−38.87	356.90
Osmium	22.48	2700	5500
Platinum	21.45	1755	4300
Silver	10.5	960.5	1950
Sodium	0.97	97.5	880
Wolfram (Tungsten)	19.3	3370.	5900

* at 20° C.
† estimated.

Metallurgy

An ore is a naturally occurring substance from which metals can be economically extracted. Clay, for example, is a complex aluminum silicate but since the cost of the extraction of aluminum from it is excessive, it is not yet regarded as an ore of aluminum. From the standpoint of composition, most ores can be classified in three groups: (1) native ores, which contain the metal in the uncombined or free condition; (2) oxide, hydroxide, carbonate ores; and (3) sulfide ores. The oxide ores are more easily reduced; hence carbonates and sulfides are usually heated in furnaces or kilns to convert them to the oxides. The important ores are listed in Table 5

Ores generally contain earthy material (silicates) which must be removed by preliminary treatment. The first method used to effect concentration of the ore is a density separation. The ore is finely ground and the earthy material with a density of about 3 is washed away in a water suspension. The more dense (density about 5) and faster settling metalliferous minerals remain. In the second method of concentration the finely ground ore is treated in such a manner that the heavier metalliferous particles are made

Table 50. Ores of Economic Importance

atural State of Metal	Principal Component Present	Metal Extracted
) Free		Platinum, gold, copper
) As oxide, hydroxide, or carbonate	Hematite: ferric oxide, Fe_2O_3	Iron
	Limonite: hydrated ferric oxide, $Fe_2O_3 \times H_2O$	Iron
	Magnetite: magnetic oxide of iron, Fe_3O_4	Iron
	Cuprite: cuprous oxide, Cu_2O	Copper
	Malachite: basic copper carbonate, $Cu(OH)_2 \cdot 2\ CuCO_3$	Copper
	Pyrolusite: manganese dioxide, MnO_2	Manganese
	Smithsonite: zinc carbonate, $ZnCO_3$	Zinc
	Bauxite: aluminum oxide, Al_2O_3	Aluminum
) As sulfide	Cinnabar: mercuric sulfide, HgS	Mercury
	Molybdenite: molybdenum disulfide, MoS_2	Molybdenum
	Sphalerite: zinc sulfide, ZnS	Zinc
	Galena: lead sulfide, PbS	Lead
	Chalcopyrite: cuprous sulfoferrite, $CuFeS_2$	Copper
	Stibnite: antimony trisulfide, Sb_2S_3	Antimony

) rise in a froth, while the lighter rock particles sink. The ore is mixed ito a slimy mass with water containing a froth-producing substance and laced in a tank of water containing a small amount of pine oil. Air is lown into it, and the ore particles, to which the oil adheres, are carried to ie top in the bubbles of foam. The earthy material, being wet by the ater, settles out. By this flotation process metals may be profitably ex- acted from discarded ore dumps of earlier mining operations.

The conversion of the ore, usually an oxide, to the metal is the reverse of ie chemical reaction involved in the rusting or oxidation of the metal. onsider, for example, the natural process of rusting or oxidation of alumi- um to form aluminum oxide, Al_2O_3. In reacting with oxygen, a metal sually loses electrons to the oxygen and forms positive ions:

$$Al \rightleftarrows Al^{+++} + 3\ e$$

o convert the ion in this case to the metallic state requires that three ectrons be supplied to each aluminum ion under appropriate conditions, s shown by the reverse of the half-equation above. The final step of etallurgy is therefore a man-made process in which the metallic ions are *duced* to metallic atoms, and is the reversal of the natural process of oxida- on of metals.

The reduction of metallic ions under conditions which permit economical rge-scale operation may be accomplished by one of three general meth- ds:

(1) *Electrolysis.* The electrons are supplied by an electric current which passed through a purified fused compound of the metal or through a ater solution of a soluble salt of the metal.

(2) *Reduction by a more active metal.* A metal which is a stronger reduc-

ing agent than the metal whose ions are to be reduced may be used as source of electrons. Potassium, sodium, magnesium, and aluminum a sometimes employed.

(3) *Reduction by carbon monoxide.* This substance, which is generate from charcoal or coke, is the reducing agent in the production of iron an other metals on a very large scale. One disadvantage is that the carbo dissolves in the hot metal, altering its properties.

Metallurgy of Aluminum

The reduction of metal ions to the metal by electrolysis is illustrated b the production of aluminum. The most abundant metal, aluminum, wa not prepared in the free form until early in the nineteenth century and wa very costly ($113 per pound in 1855). Aluminum is an extremely activ metal, and a strong reducing agent. To prepare it from its oxide ore (bau ite) or from other compounds by a chemical process requires a more powe ful reducing agent than aluminum. The metal was first prepared by th reduction of aluminum chloride with sodium or potassium, a difficult an costly process, for the metals employed had to be prepared by electrolys of their fused salts.

An efficient and low-cost method of production, essentially the one i use today, was developed in 1886 by Charles M. Hall, who had recentl been graduated from Oberlin College. The unique properties of aluminu and the stability of its compounds were known to Hall, who realized th possibilities and the need for an electrolytic process. Aluminum meta cannot be electrolytically deposited from water solutions of its salts. An aluminum oxide, which Hall was using, does not melt at a sufficiently lo temperature for effective electrolysis. He had to find, therefore, a low melting substance in which the oxide was soluble. After considerabl search he found that the alum num oxide dissolves in molte cryolite, an unusual ice-lik fluoride of aluminum and so dium found only in Greenland When he sent the electric cu rent through this solution, h obtained metallic aluminum a the negative pole.

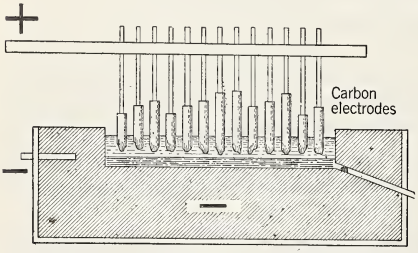


FIGURE 310. THE ELECTROLYTIC PREPARATION OF ALUMINUM

In the production of alum num by this electrolytic pr cess, cells of the type shown i Figure 310 are used. The pos tive electrode consists of carbon rods; the negative electrode is the iro box container; and the bath consists of a 10 to 20 per cent solution o purified aluminum oxide in fused cryolite. At the negative electrode o

cathode the aluminum ions are reduced to the metal which collects on the bottom:

$$Al^{+++} + 3\,e \longrightarrow Al$$

At the positive electrode or anode, oxide ions give up their electrons (are oxidized), forming oxygen:

$$O^{=} \longrightarrow O + 2\,e$$

The oxygen immediately combines with the hot carbon of the anode to form carbon monoxide, which burns to carbon dioxide as it escapes.

The production of aluminum in the United States for the year 1948 was about 630,000 tons, and the price of the ingot metal was seventeen cents per pound. The uses of aluminum (mentioned elsewhere) are based upon low cost, low density, high strength of alloys, and resistance to continued corrosion. Aluminum is self-protecting, for a thin transparent film of the oxide forms on a fresh surface of the metal and protects it from further action of the atmosphere.

Reduction by Metals

Manganese and chromic oxide are sometimes reduced by a more active metal, such as aluminum, in preference to carbon, which may combine with or dissolve in the metal produced:

$$2\,Al + (Cr^{+++})_2O_3 \rightleftarrows Al_2O_3 + 2\,Cr$$

This method is not used in any large-scale metallurgical operations, as the metal reducing agent is too costly. It is sometimes used for smaller-scale production of metals like manganese and some of the non-metals such as silicon and boron. Aluminum powder is preferable for many reductions of this type. Mixed with ferric oxide it is known as *thermit* and is used for welding. An enormous amount of heat is generated by the reaction:

$$2\,Al + Fe_2O_3 \longrightarrow 2\,Fe + Al_2O_3 + \text{heat}$$

so that the iron set free is molten and will flow into the fracture to be welded.

Reduction by Carbon Monoxide—Metallurgy of Iron

Of all metals iron is by far the lowest in price and is produced in the largest quantities. The various oxides of iron — hematite, limonite, and magnetite — are the principal ores. The chief sources of ores in the United States are in the Lake Superior area and in Alabama. The ores are associated with various "earthy" materials, such as silica or silicates and alumina. The reduction of iron ore is carried out in blast furnaces, which can be seen on the horizon of many large industrial centers. The blast furnace is charged at the top with iron ore, coke, and limestone (see Figure

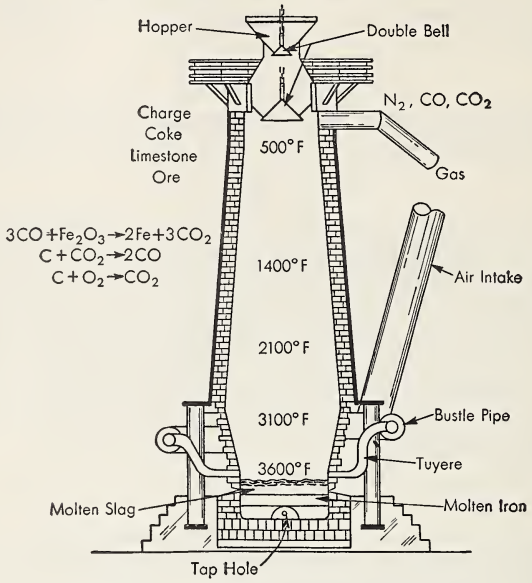


FIGURE 311. A BLAST FURNACE FOR IRON

311). The coke performs two functions: (1) it supplies heat, since the re duction of ore takes place rapidly only at high temperatures; and (2) forms carbon monoxide which is the reducing agent. A blast of pre-heate air, which enters at the base of the furnace, is also essential. The principa reactions involved in the formation of iron are:

(1) Combustion of the carbon forms carbon dioxide and liberates heat

$$C + O_2 \longrightarrow CO_2 + 94{,}450 \text{ calories}$$

(2) The liberated heat raises the contents, including the unchanged ca bon, to a high temperature. Under these conditions the carbon dioxide reduced to carbon monoxide, CO, a gaseous and vigorous reducing agen

$$C + CO_2 + 42{,}000 \text{ calories} \longrightarrow 2\ CO$$

This reaction takes place in a zone slightly above the region where th combustion to carbon dioxide occurs.

(3) The hot, gaseous carbon monoxide ascends through the furnace an reduces the iron oxide to metallic iron:

$$Fe_2O_3 + 3\ CO \longrightarrow 3\ CO_2 + 2\ Fe.$$

$$(Fe^{+++})_2\left[:\ddot{O}:\right]_3 + 3\left[:C:::O:\right] \longrightarrow 2\ Fe + 3\left[:\ddot{O}::C::\ddot{O}:\right]$$

The iron accepts three electrons per atom to form neutral atoms of metallic iron.

(4) The metallurgist calls the limestone a *flux* or *slagging agent.* Its unction is to combine with the silica by forming calcium silicate or slag, iseful in the preparation of Portland cement:

$$CaCO_3 + SiO_2 \longrightarrow CO_2 + CaSiO_3$$

As the blast furnace operates, two liquid layers collect in the bottom of he furnace. The lower layer consists of *pig iron*, the upper layer of slag. The pig iron can be used in the crude state, but most of it is further refined nd treated to form the *steels* of commerce.

Production of Steel

The iron produced in the blast furnace contains many impurities and is veak and brittle. It cannot be hammered, rolled, or pressed. The liquid netal is poured into forms, such castings being known as *cast iron* or *pig ron.* The properties which are desirable — namely, bending without racture (malleability), hardness, and high tensile strength — are obtained y treatments which convert the pig iron into steel. The difference in omposition between these two types of impure iron is the degree to which he two main impurities, carbon and silicon, are present. Generally, one nay define cast iron and steel on the basis of the carbon content. Cast ron contains above 2 to 4 per cent of carbon and other impurities such as ilicon; steel contains 0.05 to 1.80 per cent of carbon. The principal hange in effecting the conversion of pig iron to steel is the removal of he silicon and part of the carbon from the pig iron. The *open hearth* rocess is used to produce most of the steel.

In the open hearth process refining of the pig iron is accomplished by eating the molten pig iron with iron ore (Fe_2O_3), limestone, and steel crap. The furnace is a rectangular brick structure usually having a capacty of 100 tons. The refining of the impure iron requires 10 to 11 hours per harge, and is therefore a controllable process. Samples of the metal and he slag are removed and tested in order to determine the degree to which ilicon, manganese, sulfur, and phosphorus have been removed, and the lesirable drop in the carbon content obtained. The essential reaction is etween the iron oxides (from the ore and steel scrap) and the impurities esulting in the formation of a slag containing oxides, sulfides, phosphates, nd silicates. When the desired composition has been reached, the metal s removed with ladles and poured into ingots. During this step other lements may be added to produce the various types of steels. Open earth steel is used for structural work (buildings, bridges, cars, ships), prings, boilers, rails, and the many types of alloy steels.

Alloys

Only a few metals such as copper and wolfram (tungsten) are used in pure form — they are usually alloyed with other metals. Pure iron, fo example, is seldom used outside of a chemical laboratory. What we spea of as iron and steel are mixtures or combinations of iron, carbon, and on or more metals, principally manganese, chromium, nickel, and wolfra By melting together the components and then allowing the melt to solidify there results an alloy that is a coherent metallic mass, homogeneous i appearance, in many cases having some properties quite different from an one of the components. Classified by the manner in which the component blend, there are three types of alloys:

(1) The metals may form a *mechanical mixture*, in which crystals of on component may be buried in a matrix of the other substances. Alloys o this type usually have low melting points. Solder, an alloy of tin and lead and Babbitt, a mixture of antimony and lead, are examples of this class.

(2) The components may dissolve in each other while in the molten con dition, and remain in the same state of dispersion upon solidificatio One of the brasses with a ratio of copper to zinc greater than 64:34 is a example of a *solid solution*. Where the solubility of one component in an other is limited and it is present in excess, a mixture of the solid solutio and a component may result.

(3) The components may react to form an *intermetallic* compound. Th properties of such compounds are invariably different from those of th original metals. Copper and tin, for instance, can form a compound wit the formula Cu_3Sn. The great hardness of bronze as compared to eithe copper or tin is due to the presence of this compound. Alloys containin intermetallic compounds may form either solid solutions or mechanica mixtures.

There are two principal reasons for alloying a metal with other metals

(1) *To reduce the cost of production of an article.* Thus brass, an alloy o copper and zinc, costs less than pure copper, since zinc is considerably cheaper than copper. Aside from the introduction of cheaper metals alloys are often cheaper to fabricate than pure metals. For instance, it i very difficult to make castings of pure copper or aluminum, but casting are easily made from their alloys.

(2) *To modify certain properties of the metal so as to make it more useful* In alloys, desirable properties may be increased and undesirable properties decreased. Thus an alloy of copper, chromium, and a small amount o silver is harder than ordinary steel. Aluminum and magnesium are both structurally very weak, while an alloy of aluminum with four per cen magnesium has twice the strength of either metal alone.

In view of the definition that has previously been given for an alloy — a mixture of two or more metals which appears homogeneous to the eye — it

ay seem strange that steel should be referred to as an alloy. However, e carbon combines chemically with the iron to form a compound called mentite, Fe_3C, a substance characterized by great hardness and brittle-ss. Hence steel can be considered to be an alloy of iron and a carbon mpound of iron. The great difference in properties of iron and steel can attributed to the effect of the cementite.

Table 51 gives some of the more common alloys and a statement of their neral composition, together with their significant properties and uses.

TABLE 51. CHARACTERISTICS OF SOME COMMON ALLOYS

Name	General Composition in Per Cent	Valuable Properties and Characteristic Uses
minum asting alloy..	Aluminum.....85–87 Iron and silicon.....2.0 Magnesium.....0.4 Copper.....9–11	Light weight; relative high strength; pistons in automobile engines.
ralumin.....	Aluminum.....92 Copper.....4 Magnesium.....0.20–0.75 Manganese.....0.40–1	Can be rolled into sheets; very high tensile strength; desirable appearance; light in weight; used in airplane construction.
ass.....	Copper.....70 Zinc.....30	Cheaper than copper and superior to it in strength, ductility, and hardness; can be shaped by rolling, drawing, or casting; light fixtures, table lamps, gun cartridges, plumbing fixtures.
onze.....	Copper.....92–97 Tin.....1–8 Zinc.....0–2	Very resistant to corrosion; easier to cast than copper; coinage, statuary.
romel.....	Nickel.....61 Iron.....23 Chromium.....16	High electrical resistance; resistant to corrosion at high temperatures; a common heating element in electrical heating devices such as toasters.
wmetal.....	Magnesium.....88–96 Aluminum.....4–12 Manganese.....0.1–0.30	The lightest structural metal yet available; can be shaped by extrusion or casting; various parts of airplanes.
d, jewelry...	Gold.....75–84 Copper.....24–16	Desirable color; resistance to corrosion; harder than pure gold.
d, white.....	Gold.....75–85 Nickel.....8–10 Zinc.....2–9	Resembles platinum in appearance; used in jewelry.
ar.....	Iron.....64 Nickel.....36 Carbon.....0.2	Same coefficient of heat expansion as glass; used for the "lead-in" wires in electric light bulbs.
n, cast.....	Iron.....92–95 Carbon.....2–5 Sulfur, Manganese, Phosphorus, Silicon } Varying	Very hard, brittle, non-elastic, relatively low melting point compared with pure iron; cheapest form of iron; cheap castings.

Name	General Composition in Per Cent	Valuable Properties and Characteristic Uses
Sterling silver...	Silver.....92.5 Copper.....7.5	Desirable appearance; great resistance to c rosion; harder than pure silver; jewelry, silv ware.
Steel, soft.....	Principally iron, with less than 0.8% carbon	Very ductile; resistant to shock; very so rather high tensile strength; wire, structu steel, rails.
Steel, hard.....	Principally iron, with more than 0.8% carbon	Very hard; high in tensile strength; can be he treated to make it very hard; tools, cutlery.
Steel, stainless..	Iron.....75–79 Chromium.....17–19 Nickel.....7–9 Manganese.....0.6 Silicon.....0.1–0.2	Very desirable appearance; very resistant corrosion; very high tensile strength; ligh weight construction of aeroplanes; high-spe trains; architectural purposes.
Steel, manganese	Iron.....88–89 Carbon.....1–1.4 Manganese.....10	Unusually hard; burglar-proof safes, rail cro overs.
Steel, high-speed tool.....	Iron.....74–75 Tungsten (Wolfram)...18 Chromium.....4 Vanadium.....1 Carbon.....0.7	Unusually hard and retains this hardness unc unusually severe conditions; used to ma heavy-duty machine tools.
Steel, spring....	Iron.....92–97 Silicon.....1.8–2.2 Manganese.....0.6–0.9 Carbon.....0.5–0.65 Chromium.....1.0 Vanadium.....0.15	Very elastic; used to make railway-car a automobile springs.

Corrosion of Metals

A metal which has high chemical activity is usually attacked by t atmosphere, or corroded at a faster rate than a metal with a low activit The environment to which metals are commonly exposed is the atm phere, whose active chemical components are oxygen, water, and carb dioxide. The rusting of an iron fence or bridge (a very common exam of the corrosion of iron) is not a simple process of union of iron with oxyg to form iron oxides. The process is complex, requiring the presence moisture and hydrogen ion, while the non-adhering iron rust is a mixtu of various oxides and carbonates of iron. The relation of activity to t ease of corrosion holds if the oxide formed is non-adhering, that is, if t rust scales off to expose always a new surface to chemical action. Th both copper and gold are low in the activity series and corrode slow under ordinary atmospheric conditions. This relation does not hold if t rust adheres tenaciously to the metal. For example, aluminum and zi are more active than iron, yet they corrode less readily than iron because t first fine film of oxide which forms on exposure adheres to the metallic su

ıce and acts as a protective coating against further chemical attack. On ıe same principle there has been developed a method of protecting iron late by dipping it in molten zinc, whereby "galvanized iron" is produced.

The annual monetary loss of metals by corrosion is estimated at 2.5 illion dollars. A realization of this loss has led to the development of umerous methods for checking corrosion, and to extensive research work ır a better understanding of its mechanism. The attempt to develop loys which are resistant to corrosion has met with some success. How-ver, this is not a complete answer to the lowering of the corrosion rate metals, since the cost of alloys is often higher than that of the prin-pal metals. Moreover, alloys, including the so-called stainless steels, ndergo corrosion at a slow rate.

At present the method most widely used to lower the rate of corrosion of etals such as iron is the use of protective coatings. The most common these are: (*a*) Certain metals, (*b*) metallic oxides or other adhering com-ounds, and (*c*) paints and varnishes. Iron is coated by dipping it into olten tin to form "tin plate," into molten zinc to form "galvanized" on, or into lead-tin alloy to form "terne plate." Metal coatings of nickel, ıromium, cadmium, lead, copper, silver, gold, and other metals and alloys e made by electrodeposition. The article to be covered becomes the cath-le (negative), while the metal to be deposited forms the positive electrode anode. Other methods of applying metal coatings are by spraying the ırface with molten atomized metal and by vaporizing the metal in a par-ally evacuated system. The coating of aluminum with a film of oxide by ıodizing has already been mentioned. The same process may be ap-lied to magnesium and magnesium alloy castings. Iron is sometimes ated with an adhering magnetic iron oxide (gun blue coating) or with ı insoluble phosphate.

Paints, varnishes, and baking enamels are the most widely used protec-ve coatings. The use of paints and varnishes is too widely known to need ıy elaboration. Enameled coatings, porcelain, or synthetic resins ad-ixed with pigments find extensive application to refrigerators, stoves, ble tops, and kitchen and bathroom utensils.

SUMMARY

. The motivating factor in scientific work is often intellectual curiosity rather than the desire to create something of practical value. The discovery of the inert gases is an illustration.

. The electronic structure of the inert gases is unique and forms the basis for studying the structures and properties of all other elements.

. The non-metals are found in the upper right-hand portion of the periodic table. They are usually gases or volatile solids and gain electrons to form negative ions.

4. All the non-metals form hydrogen compounds, some of which are acidic water solution.
5. Some common acids are: boric (H_3BO_3), carbonic (H_2CO_3), nitric (HNO sulfuric (H_2SO_4), phosphoric (H_3PO_4), and hydrochloric (HCl).
6. Salts are compounds containing a metal and a non-metal or a non-met oxygen ion. They may be formed by neutralization, or in some cases, direct combination of the elements.
7. Metals are elements whose atoms have relatively few (one, two, or thr outer valence electrons which they more or less readily lose to form positi ions.
8. Metals form hydroxides. They have distinctive physical properties whi include high density, ductility, malleability tensile strength, and hardnes
9. Ores may contain the free metals or metallic compounds, such as oxid carbonates, or sulfides. They are usually concentrated by sedimentation oil-flotation processes.
10. Metallurgical operations are mostly reduction processes in which the electr source may be the electric current, an active metal, or carbon monoxide.

STUDY EXERCISES

1. Explain why the discovery of the inert gases was not made until co paratively recently.
2. In the following column a list of ions of elements appears. Place after ea ion the name of the inert gas whose electronic configuration it resemb (use the Periodic Chart, pages 522–523).

Li^+	K^+
Na^+	Ca^{++}
F^-	Br^-
Mg^{++}	Al^{+++}
Cl^-	I^-

3. Why is ordinary salt indispensable in the diet of every mammal? How salt obtained in primitive civilization? How is it obtained in the Unit States? Why is it such an important commodity commercially?
4. Explain why molecules of the inert gases are monatomic while the molecu of the non-metals are polyatomic.
5. Compare the electronic structures of calcium, argon, and sulfur. Which a metal? A non-metal? Would you expect calcium and sulfur to react w each other chemically if an intimate mixture were made? Explain. Wh would be the product of the reaction?
6. Derive an electronic formula for hydrogen sulfide. What would be t ordinary chemical formula? To what common compound would it be lated?
7. Before each item listed below mark: *N*, if the statement is true of no metals only; *M*, if the statement is true only of metals; *B*, if the stateme

is true both of metals and non-metals; and *I*, if the statement is true only of the inert gases.

.... Are good conductors of heat and electricity.
.... Form oxides which are acidic.
.... Form oxides which are basic.
.... Are malleable.
.... Are brittle if in the solid state.
.... Possess both positive and negative valences.
.... Form salts.
.... Have relatively few valence electrons.
.... Have complete valence shells.

8. Listed below are certain properties of metals which determine many of their uses:

(*a*) Low density
(*b*) High electrical conductivity
(*c*) High electrical resistance
(*d*) High ductility
(*e*) High tensile strength
(*f*) High coefficient of expansion
(*g*) Liquid at ordinary temperatures
(*h*) Low melting point
(*i*) Great resistance to corrosion
(*j*) Attractive luster and color
(*k*) High thermal conductivity
(*l*) High melting point
(*m*) High density
(*n*) High fluidity when melted
(*o*) A catalytic agent

Below are listed some of the common uses of familiar metals and alloys. Associate by letter the properties which are responsible for these applications.

.... Wolfram in electric light bulbs.
.... Copper for electrical power cables.
.... Aluminum for cooking vessels.
.... Aluminum for busbars on electric switchboards.
.... Aluminum alloys for constructing airplanes.
.... Nickel or nickel plate car bumpers and bathroom fixtures.
.... Bronze in statuary.
.... Mercury in thermometers.
.... Mercury in barometers.
.... Gold in jewelry.
.... Use of platinum in the manufacture of sulfuric and nitric acids.
.... Soft steel cables for suspension bridges.
.... Steel rails made by rolling.
.... Use of tinplate for "tin" cans.
.... Use of tin foil to preserve food.
.... Use of zinc to make galvanized iron.
.... Use of stainless steel for entrance to public buildings and for architectural decorative purposes.
.... Silver in silverware.
.... Chromium in stainless steel cutlery.
.... Use of pig iron (cast iron) to make an engine block for an automobile.
.... Use of a tin-lead alloy for soldering.
.... Application of both tin and zinc to iron sheets by dipping.

9. What method of reduction would be employed in the metallurgy of each the following? sodium, nickel, gold, mercury, lead (occurs as sulfide).
10. Explain on the basis of electronic structure the thermal and electrical co ductivity of metals.

FOR FURTHER READING

1. Hatcher, W. H., *An Introduction to Chemical Science.*
The inert gases are discussed on pages 135 and 150, oxygen in Chapter nitrogen and phosphorus in Chapter 14, sulfur in Chapter 11, chlorine Chapter 9, and the metals in Chapter 18.
2. Strong, Ralph K., *Chemistry for the Executive.*
The oxides of non-metals and metals are discussed in Chapter 2; silicon a its compounds in Chapter 9.
3. Babor, J. A., *Basic College Chemistry.*
The inert gases are discussed on page 314, oxygen in Chapter 5, nitrogen Chapter 20, phosphorus in Chapter 24, chlorine in Chapter 10, and the met in Chapter 31.
4. Briscoe, H. T., *College Chemistry.*
The inert gases are discussed on pages 240–244, oxygen in Chapter 4, nitrog in Chapter 28, phosphorus in Chapter 31, and chlorine and its compounds pages 262–268.
5. Hildebrand, J. H. *Principles of Chemistry.*
A good discussion on the structure of inert gases is given on page 84, and discussion of metals on pages 92–93 and 317–320.
6. Tilden, William A., *Chemical Discovery in the Twentieth Century.* Londo G. Routledge and Sons, 1936.
This book gives selected biographies of eminent scientists. The work Ramsay will be found on pages 273–288.
7. Slosson, Edwin Emery, *Creative Chemistry.* New edition revised; N York: D. Appleton-Century Company, 1930.
This book has inspired a generation of American chemists. It is very g for the general reader. Chapters 4 and 5 deal with nitrogen and its compoun

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Carbon — The Energy Carrier of Life

IN PRECEDING CHAPTERS the geologic processes were discussed first as involving alterations of various earth features and later as involving alteration of the inner structure of the constituents of the rocks. The latter was done in terms of the fundamental concepts of chemistry. It was shown that the compounds composing the earth's crust are mostly silicates. These compounds did not originate in life processes and have been designated *inorganic* substances.

However, in this planet we find the phenomenon of life, which involves far more complex organization of matter. Morphologically we find more numerous forms in living things than in inert inorganic structures. Analyzing the constitution of living things we find many more numerous compounds. On further analysis, we find that nearly all these compounds contain principally the element carbon (together with hydrogen); we find that carbon is not only the structural element of life but also, dynamically, the energy carrier of life. We shall begin by considering the latter process first.

Photosynthesis

The organic world is composed of plants and animals, which are widely distributed on the continents and in the oceans. The animals, unable to synthesize their food directly from inorganic matter, depend directly or indirectly on plants. While animals must search for food, green plants perform on a vast scale the chemical synthesis which may be considered the basis of life on the earth, and through which living matter is created by the energy of the sun. The leaf of a plant is perhaps the most wonderful chemical apparatus in existence; it has a flat, thin blade supported by a small stemlike structure, the *petiole*. The upper and lower surfaces of the leaf are covered by protective epidermal (skinlike) cells. The lower epidermal cells have slits or air pores called *stomata* (mouths), through which gases pass in and out. The cells of the middle part of the leaf contain a green pigment called *chlorophyll*, the catalyst of the chemical reaction of food synthesis. In this reaction, carbon dioxide from the atmosphere

passes through the stomata to the cells which contain chlorophyll; wat is delivered from the soil through the system of roots, stem, and vein Radiation from the sun in the presence of chlorophyll converts the carbo dioxide and water to the sugar glucose. Since energy in the form of ligh is required, the process is called *photosynthesis*. The overall chemical r action may be written thus:

$$\text{Radiation} + 6\,CO_2 + 6\,H_2O \xrightarrow{\text{Chlorophyll}} \underset{\text{Glucose}}{C_6H_{12}O_6} + 6\,O_2 \quad (1$$

As shown in this equation, oxygen is liberated in the process of photosyn thesis. The amount of glucose formed increases in sunlight and decrease in the shade, and it is not formed at all in total darkness. An increase i the quantity of available carbon dioxide up to a certain point also produc an increase in the quantity of sugar. As fast as the sugar is formed, it converted by enzymes to starch, which is stored in the leaf. During th night the excess starch stored in the leaf is reconverted to sugar, passe down to the stem and roots, and is there reconverted to starch. The r versible conversion of glucose to starch by enzymes is an example of th union of several reactive molecules with themselves to form a giant mol cule which is relatively stable; the process is called *polymerization*:

$$\underset{\text{Glucose}}{nC_6H_{12}O_6} \underset{\text{depolymerization}}{\overset{\text{polymerization}}{\rightleftharpoons}} \underset{\text{Starch}}{(C_6H_{10}O_5)} + nH_2O$$

The plant cells utilize the sugar molecules to build the other compound necessary for the living functions. For example, *cellulose*, the hard fib of plant tissues, is built up by symmetrical combination of glucose mol cules. Starch and cellulose therefore have the same chemical composition both yield glucose on hydrolysis. The difference in the arrangement o the glucose "blocks" accounts for the difference in their properties.

Most of the sugars, starches, and celluloses have a general compositio which may be expressed by the general formula $C_x(H_2O)_y$, and hence the are called *carbohydrates*; i.e., hydrates of carbon. From the carbohydrate (the initial products of photosynthesis) the living cells by enzymatic chem cal reactions synthesize other organic compounds required in the variou functions of the cells. Two important classes of compounds are recognized *fats* and *proteins*. Fats, like carbohydrates, are primarily fuels and contai carbon, hydrogen, and oxygen. The proteins contain nitrogen in additio to carbon, hydrogen, and oxygen, and sometimes they also contain sma amounts of sulfur and phosphorus. The nitrogen, sulfur, and phosphoru are derived from the various inorganic ions (NO_3^-, $PO_4^{\equiv}$, $SO_4^{=}$, etc.) whic are taken in solution from the soil. Thus the living cell, working primaril with four elements (carbon, oxygen, hydrogen, and nitrogen), is able to buil up the many organic compounds which are found in plants and animal

The overall photochemical reaction, which produces glucose, and which shown by equation (1), starts with carbon dioxide and water and *requires* ergy in the form of radiation. These initial substances are products of idation of the respective elements carbon and hydrogen, and both have tually *zero* potential energy with respect to union with oxygen, since ge amounts of heat are *liberated* in their formation from the elements. e complete combustion of 12.010 grams of carbon to form 44.010 grams carbon dioxide (1 mole) liberates 94,450 calories of heat energy:

$$C + O_2 \longrightarrow CO_2 + 94{,}450 \text{ calories} \quad (2)$$

e formation of two moles of water (36.0320 g) is accompanied by the eration of 117,300 calories, or 58,650 calories per mole:

$$2\,H_2 + O_2 \longrightarrow 2\,H_2O \text{ (vapor)} + 117{,}300 \text{ calories} \quad (3)$$

e product of photosynthesis, glucose, contains a considerable amount of mical energy, for when it is burned or oxidized 675,000 calories of heat mole of glucose is liberated:

$$C_6H_{12}O_6 + 6\,O_2 \longrightarrow 6\,CO_2 + 6\,H_2O + 675{,}000 \text{ calories} \quad (4)$$

uation (4) is the reverse of equation (1). It therefore follows that otosynthesis, in which completely oxidized substances undergo chemical nges to produce an oxidizable substance, must involve *reduction* of one more of the initial substances. It is known, and will be apparent later this chapter, that in the formation of glucose from carbon dioxide, bon undergoes only partial reduction. Thus, by means of solar energy l chlorophyll, substances of low chemical energy content are converted substances of higher energy content and these in turn may be oxidized produce heat energy.

piration

The animal body is not unlike a machine. It obtains energy by the dation of carbon compounds — mostly carbohydrates and fats which e a higher energy content than the resultant products of the oxidation, bon dioxide and water. The combustion, as shown in equation (4), ases heat and other forms of energy and is the reverse of the equation photosynthesis (1). For example, the carbohydrates in digestion are verted to glucose, which passes through the intestinal wall into the ph and blood and is taken to the liver, where it is changed to glycogen imal starch). About 0.1 per cent of glucose remains in the blood, ich is the circulating medium. In the various tissues heat energy is duced by enzymatic oxidation; as more glucose is required, glycogen hanged to glucose. The burning of glucose, then, is somewhat analogous the combustion of gasoline in the automobile engine. Both are fuels, h contain carbon compounds, and both undergo oxidation to give

carbon dioxide, water, and heat. The combustion in the metallic eng is explosive and at a high temperature; the oxidation in the "protein c verter" is quiet, and in the human body proceeds at a temperature 37° C. (98.6° F).

Body temperature varies within narrow limits irrespective of the us external temperature conditions; this indicates that combustion so where within the body must furnish heat. In addition, energy is requi for the normal processes which keep the body alive. A young man wei ing 70 kilos (154 pounds) requires about 70 Calories [1] per hour or 1 Calories per 24 hours. For greater activity or work, more energy required. For light work, 75 Calories per hour, and for hard work, 150 300 Calories per hour must be available. It is clear, therefore, that animal body is able to convert chemical energy to heat and mechani energy; this is accomplished by respiration or the reversal of the fun mental chemical process of photosynthesis. The system *carbon dioxi water* $\rightleftarrows$ *organic compounds* is a means for transforming radiant energy fr the sun to heat energy and distributing it as required by the animal bod

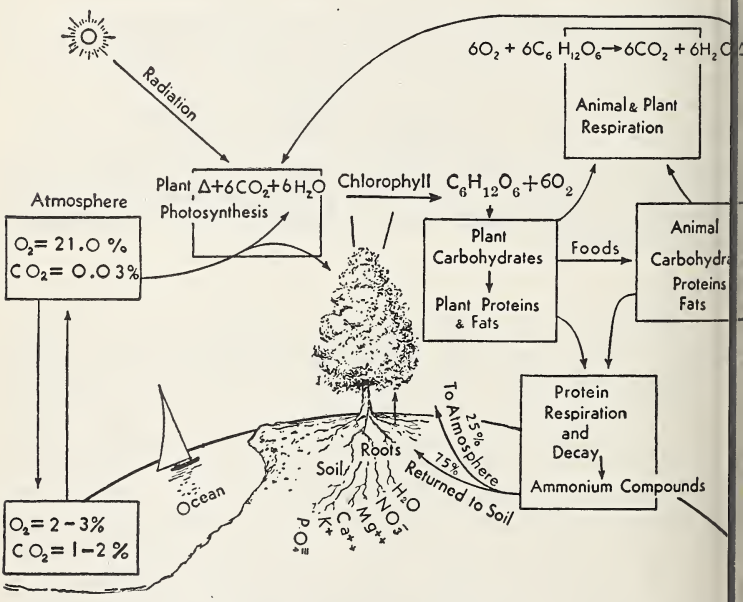


FIGURE 312. THE ROLE OF CARBON AS THE ENERGY CARRIER OF LIFE
The cycle of the most important elements in living organisms

[1] This is a kilogram calorie, which is 1000 times larger than the ordinary calorie.

Respiration in plants involves oxidation of carbon compounds by living ells. Plants take in oxygen chiefly through the stomata of the leaf, but lso through the stem and roots. During the oxidation changes, carbon ioxide and water are produced, as in the animal tissues; these waste prodcts are eliminated chiefly through the stomata of the leaves. In plants, espiration takes place day and night, but photosynthesis only in light; in nimals only respiration takes place. Therefore respiration covers all the omplex chemical changes which occur in the living cells, in which atmosneric oxygen is used, organic compounds are oxidized, and carbon dioxide nd water are formed, accompanied by the transformation of definite nounts of chemical energy to the kinetic energy which makes life possible. he cycle is completed by photosynthesis. The products of respiration — rbon dioxide and water — are consumed, radiant energy is transformed to potential (chemical) energy; carbon dioxide is reduced; organic comounds are formed; and oxygen is set free. Thus by its oxidation-reduction lations, carbon acts as the energy carrier of life.

But the analogy of a living system to a machine breaks down at this oint. For while the gasoline fed to the car does not enter into the structre of the car, the food entering the animal system also becomes a part its structure. The instant organic (carbon) structures enter into the ving system they are transformed into a myriad of other substances, and me of them enter into the body itself by the living organism. To underand the significant role of carbon and its compounds, it will be necessary consider the structure of carbon in terms of the fundamental concepts chemistry.

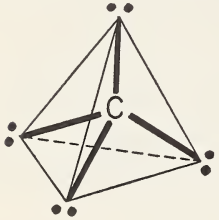
e Element Carbon

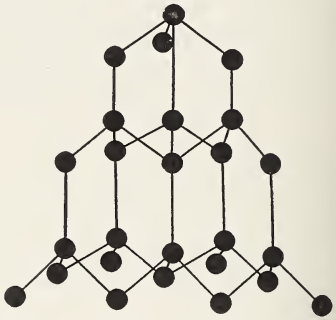
Carbon is the first element of the fourth group of the periodic table. the extreme left end of this period is the element lithium, $(Li\cdot)$, a etal, each of whose atoms readily reacts by the loss of an electron to form e ion, Li^+, while at the extreme right end of the period is fluorine, $(\cdot \ddot{F} :)$, ch of whose atoms vigorously reacts by the gain of an electron to form e fluoride ion, F^-. Carbon, which is midway between these two elents, neither loses nor gains electrons, but forms covalent compounds. aving four electrons in its outer orbit, it can therefore share four electron irs with other atoms with which it can combine. The four valence ctrons on the carbon atom are ordinarily represented on a plane surface $\cdot \dot{C} \cdot$, but these four electrons form four sets of electron pairs — with ditional electrons from other atoms — which are symmetrically arranged space at the corners of a regular tetrahedron. The electron pair bond very characteristic of all carbon compounds and is usually referred to a covalent bond. Refer to the left diagram on page 598.

Carbon atoms are able to join with each other in large aggregates which

constitute crystals of the element. Carbon is unique in that its ato may be joined to each other in compounds to form chains and rings of great number and variety, to which atoms of other elements are attache However, the ability to form stable carbon to carbon chains containi more than eight or ten carbon atoms apparently requires the presence hydrogen atoms in the compounds. Carbon thus forms a very lar number of compounds — nearly a million — more than any other eleme except hydrogen.

Elementary carbon exists in two crystalline forms, *diamond* and *graphi* In the former, each carbon atom is joined by covalent bonds to four oth carbon atoms which are symmetrically arranged around it at the fo corners of a regular tetrahedron, as shown below:

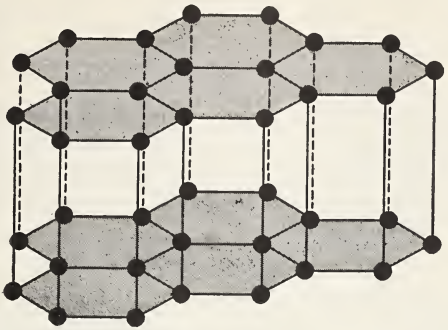




From "General Chemistry for Colleges," by Herman T. Briscoe, 4th ed., 1949. (Houghton Mifflin Company)

All the atoms in a crystal are linked together in this manner, forming large single aggregate, which is actually a giant molecule. The bindi forces between the tetrahedrally placed carbon atoms (carbon to carb bonds in *four* directions from each carbon atom) are very strong, and f this reason diamond is extremely hard — in fact, the hardest substan known. The carbon to carbon bond may be represented as C—C or C : The dash notation is commonly used, and it is understood that it denot a covalent bond of a single electron pair.

In graphite, each carbon atom is surrounded by three other carb atoms, two of which are held by the single covalent bond as in diamon but the third of which is held by what is known as a double bond, that by two electron pairs, and is represented by two dashes C = C, or by t pairs of electrons C : : C. The carbon atoms in graphite are closely h to each other within layers, as shown in the following drawing:



From "General Chemistry for Colleges," by Herman T. Briscoe, 4th ed., 1949. (Houghton Mifflin Company)

ut the layers are not strongly bound, and slip or slide over each other. or this reason graphite is a very soft substance, and is used in "lead" encils and as a lubricant. Other commercial forms of carbon such as mpblack, charcoal, and boneblack are probably composed of very small ystals of graphite.

In addition to the naturally occurring free element, diamond and graphe, carbon is found in all organic compounds, most of which were formed in ving things or from other compounds formed in life processes. The chief atural sources of carbon or organic compounds, other than living plants nd animals, are the mixtures coal, petroleum, and natural gas, all of hich are important fuels, and which are treated in the next chapter.

Chemical Properties of Carbon. Carbon, like silicon, is in Group IV of he Periodic Table, and forms compounds with elements on either side of roup IV. At room temperature, carbon is not very reactive, but at gher temperatures it combines directly with metals to form *carbides*, ith a few non-metals such as with sulfur to form sulfides, and with oxygen form carbon monoxide and carbon dioxide.

The Oxides of Carbon. The monoxide, CO, is formed when combustion carbon or carbon compounds occurs in a limited supply of air. It is esent in small amounts in the exhaust gases of automobile engines, parcularly when the engine has just been started. Carbon monoxide is a rong reducing agent, and is used in metallurgical processes to remove the ygen from metal oxide ores. It is a constituent of several fuel gases, rticularly producer gas, which is prepared by passing a limited supply of r through hot coke or coal. Water gas is prepared by passing steam rough hot coke:

$$\underset{\text{carbon (coke)}}{C} + \underset{\text{water (steam)}}{H_2O} \longrightarrow \underbrace{\underset{\text{carbon monoxide}}{CO} + \underset{\text{hydrogen}}{H_2}}_{\text{water gas}}$$

Even in small concentrations, carbon monoxide is extremely toxic, for it unites with the hemoglobin of the blood, decreasing its oxygen carrying capacity. Since carbon in carbon monoxide shares only two of its four outer electrons with oxygen, the compound can combine with additional oxygen to form carbon dioxide:

$$2\,CO + O_2 \longrightarrow 2\,CO_2 + \text{heat}$$

Carbon dioxide is a colorless gas, somewhat soluble in water. As previously shown, the solution is slightly acid, because of the formation of carbonic acid. Water charged with carbon dioxide (soda water) is extensively used in the manufacture of effervescent carbonated beverages. Carbon dioxide is liquefied, and handled in cylinders. When the gas is allowed to evaporate rapidly, it cools sufficiently so that a part solidifies. The solid compressed in blocks is known as "dry ice." Although solid carbon dioxide has been known for many years, only since 1925 has it been produced in large quantities and at a price that admits of its use as a refrigerant. Carbon dioxide passes directly from the solid to the gaseous condition, leaving no residue, and surrounds the material to be refrigerated with an atmosphere of dry cool gas. Its most extensive use is as a refrigerant in the distribution of ice cream and frozen foods and in the shipping of perishable fresh foods. Carbon dioxide is formed by the complete combustion of carbon and carbon compounds, and is liberated whenever a carbonate is treated with an acid, as:

$$CaCO_3 + 2\,HCl \longrightarrow CaCl_2 + H_2CO_3$$
$$H_2CO_3 \rightleftharpoons H_2O + CO_2$$

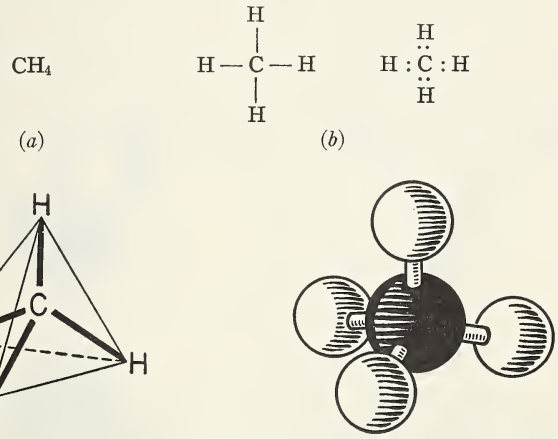
Hydrocarbons

Hydrocarbons are compounds which contain only hydrogen and carbon; a very large number of them are found in naturally occurring materials and they can also be prepared in the laboratory. Since hydrocarbons contain only the two elements, and since other types of compounds containing more elements may be prepared from them, they are regarded, formally at least, as the parent substances of all other organic compounds. The simplest hydrocarbon is methane, CH_4, which is the first member of a series of hydrocarbons in which each member differs from the next one by a CH_2 group, and all of which may be represented by the general formula $C_n H_{2n+2}$. A few of the simpler members and one of the higher members of this series, known as the methane series, together with their formulas and some of their properties, are listed in Table 52 (page 602).

It may be seen from Table 52 that the melting and boiling points gener-lly increase as the molecules become more complex. The first few mem-ers are gases at ordinary temperatures, the intermediate members are liq-ids, and the higher members are solids. Hydrocarbons occur in natural as, coal, coal gas, and petroleum. Natural gas, for example, contains 85 to 0 per cent methane, 5 to 11 per cent ethane, 2 to 5 per cent propane, 1 to 3 er cent butane, and 1 to 5 per cent of other hydrocarbons with higher arbon content. As discussed in greater detail on page 626, petroleum ields upon distillation mixtures of hydrocarbons which are known as asoline, kerosene, and lubricating oils.

Structure of Carbon Compounds. In order to explain the properties and ehavior of carbon compounds it is necessary to consider the arrangement f atoms in their molecules. For example, the information that a com-ound of carbon is composed of x number of carbon and y number of ydrogen atoms is not sufficient; it is necessary in order to describe the ompound and its properties more completely to inquire in what pattern carbon and y hydrogen atoms are arranged; in other words it is important o know besides *composition* something of the *structure* of the molecule.

The simplest compound containing carbon and hydrogen is methane. he formula of methane is represented thus:



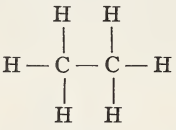
ormula (*a*) gives only the composition of the molecule, namely that it as one carbon and four hydrogen atoms in the molecule. Formulas (*b*) dicate that the carbon atom is joined to four hydrogen atoms by cova-nt bonds which are represented either by a short *dash* or by a *pair of ectrons*. Formulas (*c*) and (*d*) give a *three-dimensional structure* of the

TABLE 52. THE METHANE SERIES

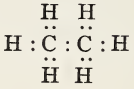
Name of Compound	Formula $C_n H_{2n+2}$	Molecular Weight	Melting Point, °C	Boiling Point, °C
Methane	CH_4	16.0	−182.5	−161.4
Ethane	C_2H_6	30.0	−183.2	− 89.0
Propane	C_3H_8	44.1	−187.3	− 42.1
n-Butane	C_4H_{10}	58.1	−138.3	− 0.5
n-Pentane	C_5H_{12}	72.1	−129.7	36.0
n-Hexane	C_6H_{14}	86.1	− 95.4	68.7
n-Heptane	C_7H_{16}	100.1	− 90.6	98.4
n-Triacontane	$C_{30}H_{62}$	422.5	+ 64.7	304.0

molecule. The carbon atom occupies the center of a hypothetical tetrahedron and the four hydrogen atoms are arranged symmetrically at the four corners of this imaginary tetrahedron. The heavy lines in diagram (*c*) represent the so-called chemical bonds or electron pairs.

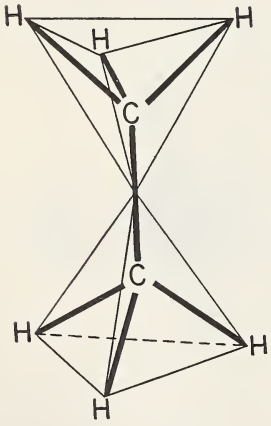
In the same manner ethane, which is composed of two carbon and six hydrogen atoms, is given the structures (*e*), (*f*), (*g*), and (*h*).



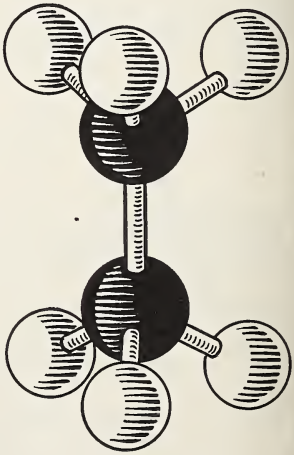
(*e*)



(*f*)

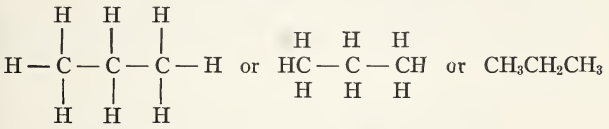


(*g*)



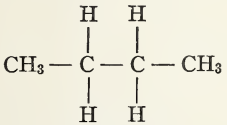
(*h*)

Note that each carbon atom uses one covalent bond to unite with the other carbon atom, leaving three bonds in each attached to hydrogen atoms. In the three-dimensional structure the two tetrahedra are shown joined at two apexes. However, with compounds which have several carbon atoms it is easier to represent the structural formulas by several types of two-dimensional structures. For example, propane, C_3H_8, can be represented as follows:

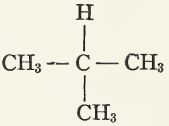


Propane

In the case of the compound with four carbon atoms, C_4H_{10}, we are presented with a new phenomenon. There are two hydrocarbons which by analysis and molecular weight determination have the formula C_4H_{10}; it can be shown that both are pure substances and not mixtures; one boils at $-10°$ C and the other at $-0.5°$ C. Moreover, they have different melting points, densities, and other physical properties. Compounds which differ in properties but with the same kind and number of atoms are called *isomers*. Each kind of butane molecule has four carbon atoms and ten hydrogen atoms. To account for the difference in properties it is assumed that they have different structures; in other words, they have different arrangements of the four carbon and ten hydrogen atoms. These differences are most simply shown as follows:

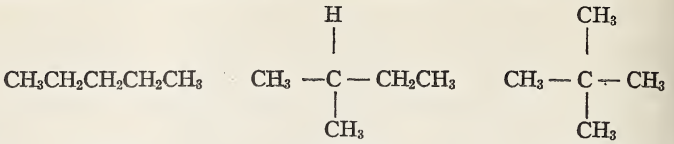


n(ormal)-Butane
(b.p. -0.5°C)



Isobutane
(b.p. -10°)

The structural theory of organic chemistry predicts only two possible arrangements for molecules which contain four carbon and ten hydrogen atoms. Isobutane differs from *n*-butane in that it has one carbon atom joined to three other carbon atoms. This agrees with the existence of only two butanes, C_4H_{10}. Similarly there are only three pentanes (C_5H_{12}) known, and the structural theory predicts also only three possible arrangements:



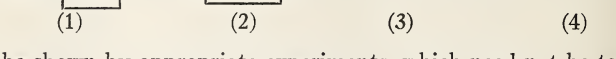
As the number of carbon atoms per molecule increases, the number possible isomers rises rapidly. Thus there are five possible isomers hexane (C_6H_{14}); there are nine for C_8H_{18}, thirty-five for C_9H_{20}, and ov 100,000 for $C_{20}H_{42}$.

Types of Hydrocarbons. The hydrocarbons considered in the precedi section, such as methane (CH_4), the butanes (C_4H_{10}), pentanes (C_5H_{12} and the like, are called *saturated hydrocarbons*; they react slowly with th common chemical reagents at room temperature; for example, they a not oxidized when shaken with one per cent solution of potassium pe manganate and do not decolorize bromine water. Similarly, they react ve slowly with concentrated sulfuric and nitric acids at room temperatur

From petroleum distillates it is possible to separate small amounts hydrocarbons in which the proportion of hydrogen in the molecule is le than in the saturated hydrocarbons. Their composition is represente by the general formulas C_nH_{2n}, C_nH_{2n-2}, etc. They are called *unsaturat* hydrocarbons. Compared with the saturated they show a *striking rea tivity*: they are oxidized easily by permanganate, and decolorize bromi water readily with the formation of definite compounds. This unsatura tion, or smaller hydrogen content, is directly connected with this striki reactivity. The first member of the unsaturated hydrocarbons, *ethe* (C_2H_4), is related to ethane, which when heated decomposes as follows:

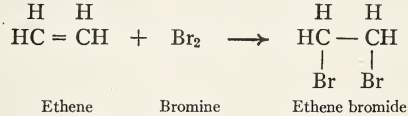
$$\underset{\text{Ethane}}{C_2H_6} + \text{Heat} \rightleftarrows \underset{\text{Ethene}}{C_2H_4} + H_2$$

The reversible reaction shows that ethene contains two hydrogen ato less per molecule than ethane. If ethene is heated under pressure wit hydrogen it is converted to ethane. Since the two hydrogen atoms we removed from the ethane molecule to produce ethene, there are two po sibilities: (*a*) the hydrogen atoms were removed from a single carbon ato as shown in formula (1); (*b*) the hydrogen atoms were removed from th *two adjacent carbon atoms* as shown in formula (2).

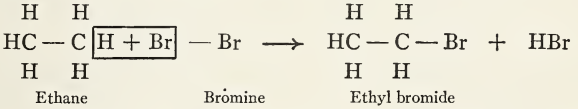


It can be shown by appropriate experiments, which need not be taken u

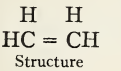
n this discussion, that the formation of unsaturation is best represented by formula (2), namely, that the elimination of the hydrogen takes place rom each of two *contiguous carbon atoms*. Further, the two odd electrons, hown as short dashes in formula (3) and produced by the elimination of he two hydrogen atoms, form a pair of electrons that is shared by the wo carbon atoms in addition to the single covalent bond of ethane. The wo dashes, called a *double bond*, shown in formula (4), indicate the sharing f two pairs of electrons; one is the normal covalent bond, and the other a pecial or more reactive chemical bond. For example, if bromine is added o ethene it is immediately decolorized with the *addition* of two atoms of romine per molecule of ethene:



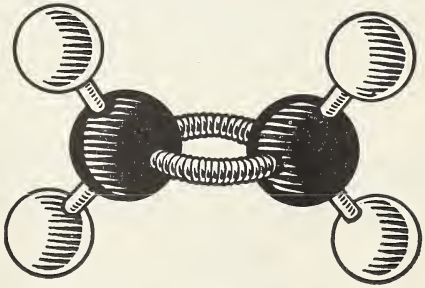
Under similar conditions bromine has no action on ethane; if heat is applied n the presence of a catalyst a reaction takes place; but it is unlike addition, or the reaction is very slow and hydrogen bromide is given off:



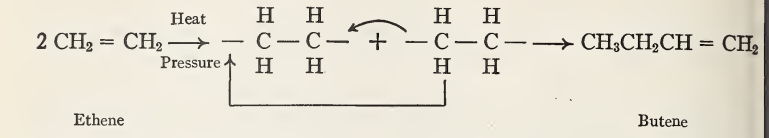
t will be noted that the reaction involves *substitution* of one hydrogen tom by a bromine atom. From this brief discussion it is evident that olecules of saturated hydrocarbons react with bromine or chlorine hrough *substitution* of the halogen atoms for hydrogen, while those with *ouble* bonds (unsaturated hydrocarbons) can form reaction products by rocess of *addition*. Therefore, the notation of a double bond in any rganic compound denotes a special type of chemical bond — unsaturation – between two contiguous carbon atoms. The structural representation f the double bond in both two-dimensional and three-dimensional space s given in the following formulas for ethene:


Structure using dash valences

Electronic structure


Three-dimensional structure

One of the most useful reactions of unsaturated hydrocarbons is *self addition* or *polymerization*. For example, when ethene is treated with a catalyst under specified conditions two molecules may combine to give a new unsaturated hydrocarbon shown schematically as follows:



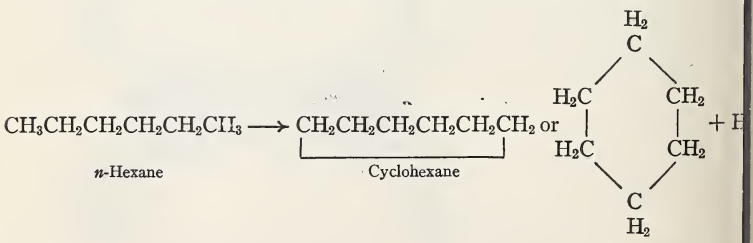
The process of self-addition can be repeated, the four carbon molecul being converted to 8, 10, 12, and finally to molecules with several thousan carbon atoms. As the molecular weight increases likewise the propertie become altered. Ethene is a gas, but the product with 6 carbon atoms is a liquid; as the molecular weight increases the product becomes a viscou oil; at this stage the *polymer*, as the product of *self-addition* is known, ca be used as a lubricating oil. With further addition and increase in molec ular weight a *waxy* product is obtained and finally a *hard translucent resin* The product is known as *polythene*.

$$n CH_2 = CH_2 \xrightarrow{\text{Heat}} (- CH_2 - CH_2 -)_n$$

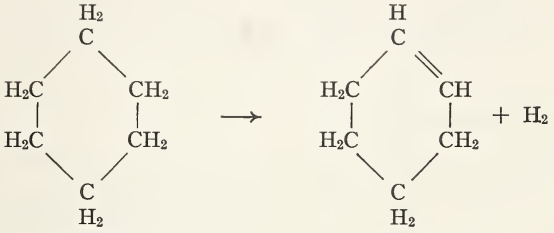
Ethene (monomer) — Polythene (polymer)

This resin when heated becomes soft and can be extruded in the form o sheets or filaments which are known as *plastics*. The filaments can b woven, knitted, braided, or crocheted into a variety of weaves and patterns while the sheets can be machined or drilled and put to a variety of uses Thus polythene plastics have been used in bottle caps, electric cables food packaging, water resistant clothing, and as interior coating for tanks kegs, and drums. Other important applications of polymerization o unsaturated hydrocarbons are those which involve the production o synthetic rubbers. The principle involved is the same, though the initia products and molecular pattern of the polymers are different.

Another class of hydrocarbons differs from the two thus far considere in that the structure is cyclic. For example, n-hexane, C_6H_{14}, can b converted under appropriate conditions to cyclohexane:

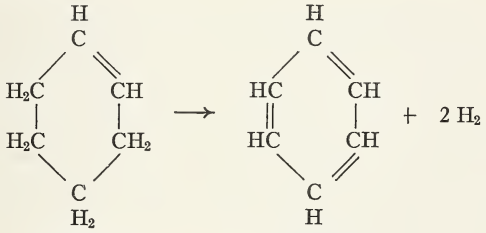


The formation can be assumed to involve the elimination of one hydrogen atom from each of the two end carbon atoms and union of the latter to form a *cyclic ring*, represented as a hexagon structure in the above formula. Though cyclohexane, C_6H_{12}, has the general formula C_nH_{2n}, it does not exhibit any unsaturated properties; this is in accordance with the cyclic structure assigned to it which shows no double bonds. Cyclohexane, however, can be converted by appropriate reaction to cyclohexene which shows unsaturated properties:



Cyclohexane — Cyclohexene

There is another class of cyclic unsaturated hydrocarbons which differs radically from cyclohexene in that its members do not show great reactivity. The simplest hydrocarbon of the class is benzene, C_6H_6, which is obtained from coal tar. Its relation to cyclohexane is shown by the following formulas:



Cyclohexene — Benzene (Cyclohexatriene)

Though the structure of benzene shows three double bonds it exhibits under ordinary conditions substitution reactions instead of addition:

$$\underset{\text{Benzene}}{C_6H_6} + \underset{\text{Bromine}}{Br_2} \xrightarrow[60^\circ]{Fe} \underset{\text{Bromobenzene}}{C_6H_5Br} + HBr$$

Under special conditions, as for example in presence of peroxides, benzene does show addition reactions, thus proving that it has an unsaturated structure:

$$\underset{\text{Benzene}}{C_6H_6} + 3\,Cl_2 \longrightarrow \underset{\text{Benzenehexachloride}}{C_6H_6Cl_6}$$

Chlorine

The addition product has been found as useful as an insecticide as DDT particularly toward flies which have developed immunity to DDT However, most of the usefulness of benzene hydrocarbons is based on its substitution reactions. For example, benzene with nitric acid is converted to nitrobenzene which on treatment with reducing agents gives aniline:

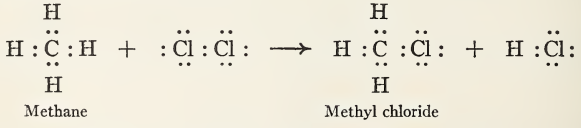
$$\underset{\text{Benzene}}{C_6H_6} \xrightarrow{HNO_3} \underset{\text{Nitrobenzene}}{C_6H_5NO_2} \xrightarrow{3\ H_2} \underset{\text{Aniline}}{C_6H_5NH_2} + 2\ H_2O$$

The above reactions are of considerable interest and importance, for they are useful in the study of a large number of compounds related to hydrocarbons.

Derivatives of Hydrocarbons

As stated in a preceding section, the hydrocarbons may be formally regarded as the parent substances of all organic compounds. It does not follow that all other organic compounds are always prepared by procedures which start with a hydrocarbon, or with a compound which was derived from a hydrocarbon. Industrial methods are governed by economic considerations, and many small-scale laboratory procedures are designed for particular purposes such as the discovery of new methods of synthesis, the development of new products, the determination of structure, or the illustration of principles. In many instances, the initial substances are not hydrocarbons.

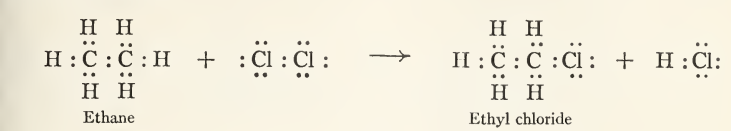
Halides. The relationship between some of the more common classes of organic compounds can be best shown by starting with hydrocarbons and carrying out a series of oxidations. In a saturated hydrocarbon like methane or ethane the electron pairs around the carbon atom are held rather closely to it, for hydrogen is the more electropositive of the two elements. When the compound is treated with an oxidizing agent, one or more of the hydrogen atoms are replaced by chlorine or other halogen atoms, oxygen atoms, or hydroxyl (OH) groups, any of which are more electronegative than the carbon:



Methane — Methyl chloride

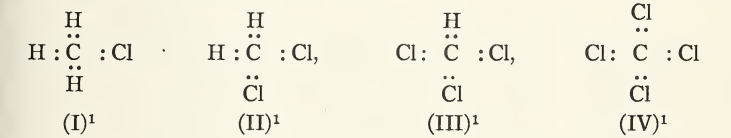
The oxidation does not involve the complete transfer of one or more electrons from one atom to another, but rather the shifting of one or more electron pairs away from the carbon and toward the more electronegative atoms of the oxidizing agent. The resulting compound is *not* ionic, but is definitely polar, in contrast to the non-polar methane (see page 541), because of the shift of the electron pair toward the chlorine atom.

Similarly, ethane yields ethyl chloride when treated with chlorine under suitable conditions:



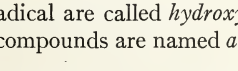
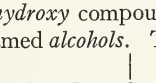
Ethane Ethyl chloride

Derivatives, like methyl and ethyl chlorides, in which a hydrogen of a saturated hydrocarbon is replaced by a halogen atom, are known as *alkyl halides*, and the group of atoms like CH_3- (methyl), C_2H_5- (ethyl), C_3H_7- (propyl), and so on, are called alkyl radicals. In the above reactions, the chlorination ordinarily proceeds further, and more than one hydrogen atom in a molecule may be replaced by the halogen, yielding compounds which are in progressively higher stages of oxidation, as indicated by the positions of the electron pairs. In the case of methane, the following compounds may be formed:



(I)[1] (II)[1] (III)[1] (IV)[1]

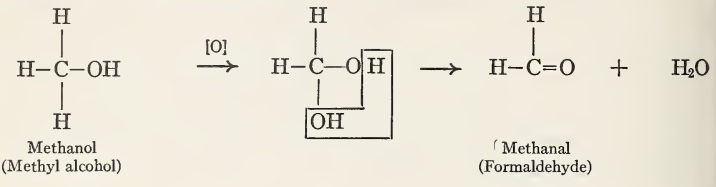
In compound (III) (chloroform) three electron pairs have shifted from the carbon; in compound (IV) (carbon tetrachloride) all four pairs have moved toward the respective chlorine atoms, and this compound is therefore at the highest possible stage of oxidation. It should be noted that the initial compound methane (CH_4) and the final product of this series of oxidations, carbon tetrachloride (CCl_4) have symmetrical and therefore non-polar molecules, while the three intermediate compounds are polar. Compounds with more than one carbon atom per molecule may consist of carbon atoms which are in different stages of oxidation, as ethyl chloride.

Alcohols. Compounds which contain the OH group attached to an organic radical are called *hydroxy* compounds. If the radical is alkyl the hydroxy compounds are named *alcohols*. They may be represented by the general formula  or  in which R represents an alkyl group. Joined to the carbon by the two open bonds may be other R's or hydrogen. There are several classes of alcohols, but only the two simplest compounds are considered here. Methyl alcohol or methanol is prepared commercially by a synthetic process in which CO (carbon monoxide) and hydrogen combine. Ethyl alcohol or ethanol is prepared

[1] Six electrons are eliminated from each chlorine atom in order to simplify the formulas.

by the fermentation of sugar, or by the addition of water to ethylene. Both represent the first stage of oxidation of one carbon atom of a hydrocarbon. Methyl alcohol resembles methane in that it is combustible, and its three hydrogen atoms may be replaced by other groups. The higher (longer chain) alcohols bear a closer resemblance to the hydrocarbons than the lower members (methyl, ethyl, and propyl). They are not, for example, as soluble in water as the lower members, for this property diminishes as the chain becomes longer.

Aldehydes and Ketones. Aldehydes may be obtained by the oxidation of alcohols of the class represented by CH_3OH and C_2H_5OH:



Methanol (Methyl alcohol) — Methanal (Formaldehyde)

Ethanol (Ethyl alcohol) — Ethanal (Acetaldehyde)

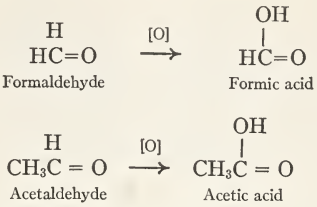
In the above equations the oxidation is interpreted as the replacement of a hydrogen atom by the OH group. The hypothetical intermediate compounds in which two hydroxyl groups are attached to a carbon atom are unstable and lose water.

The general formula for aldehydes is $RC(=O)H$. If another alkyl group (R) is substituted for the hydrogen in the aldehyde a *ketone* is obtained.

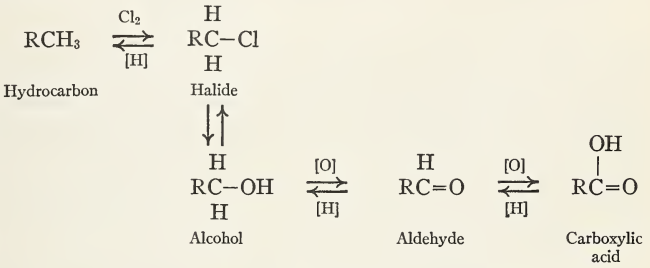
The general formula for a ketone is $R-C(=O)-R$, and a familiar example is acetone, $(CH_3)_2C=O$, which is used as a lacquer solvent. In both aldehydes and ketones the two electron pairs (double bond) have shifted away from the carbon atom and toward the more electronegative oxygen, in what is called the carbonyl group $=C=O$ or $:\dot{C}::\dot{O}:$. Aldehydes are very reactive and are readily oxidized to carboxylic acids.

Carboxylic Acids. Oxidation of aldehydes yields compounds which contain the carboxyl group ($-COOH$) and which have acid properties. In the carboxyl group, which is a combination of the carbonyl ($-CO$) and hydroxyl (OH) groups, three electron pairs have shifted away from the carbon and the carboxylic acids therefore contain at least one carbon

atom which is in the third stage of oxidation. The formation of each of the two simplest organic acids is shown in the equations:



The reactions and classes of compounds mentioned above may all be considered derivatives of a hydrocarbon $R-CH_3$ which may be methane, ethane, propane, etc.



The formal step-by-step oxidations shown above serve to introduce a number of classes of organic compounds, but it should not be concluded that all oxidations proceed stepwise. Carboxylic acids may be further oxidized to CO_2, the highest state of oxidation of carbon, and the end product in the ultimate oxidation of organic compounds. However, a hydrocarbon may be simply burned to CO_2 without producing any of the intermediate products:

$$2\,C_2H_6 + 7\,O_2 \longrightarrow 4\,CO_2 + 6\,H_2O$$

The hydrocarbons are excellent fuels and contain a high amount of potential chemical energy which diminishes step by step as the oxidations described above proceed, and the final product, CO_2, has a very low potential chemical energy. The process of photosynthesis described earlier in this chapter brings about the reverse process — reduction. Carbon dioxide is reduced and the products of photosynthesis — sugars, fats, etc. — all possess chemical potential energy.

The simpler compounds which are derived from the hydrocarbon ethane are summarized in Table 53.

Table 53. Simpler Derivatives of Ethane CH_3CH_3

Functional Group joined to ethyl radical CH_3CH_2-		Name and Formula of Derivative		Class of Compound
Chloro	— Cl	CH_3CH_2Cl	Ethyl chloride	Halides
Bromo	— Br	CH_3CH_2Br	Ethyl bromide	Halides
Iodo	— I	CH_3CH_2I	Ethyl iodide	Halides
Amino	— NH_2	$CH_3CH_2NH_2$	Ethyl amine	Amino
Hydroxyl	— OH	CH_3CH_2OH	Ethyl alcohol	Alcohols (hydroxy)
Cyano	— CN	CH_3CH_2CN	Ethyl cyanide	Cyanides
Nitro	— NO_2	$CH_3CH_2NO_2$	Nitroethane	Nitro compound
Functional groups obtained by oxidation of the — CH_2 part of the Ethyl radical				
Aldehyde	— CHO	CH_3CHO	Ethanal (acetaldehyde)	Aldehyde
Carboxyl	— COOH	CH_3COOH	Ethanoic acid (acetic acid)	Carboxylic acid

Inspection of the above table will show that if a hydrogen atom is removed from ethane, the remainder part of the molecule C_2H_5-, is called the *ethyl radical*. By joining the radical with various *reactive* or *functional* groups such as Cl, Br, OH, NH_2, etc., the various types of derivatives of the hydrocarbons are obtained. In some cases, however, it is not possible to obtain the derivative directly by substitution, that is, by removal of a hydrogen atom and introduction of the functional groups in its place. For example, the following reaction is not practical:

$$\underset{\text{Ethane}}{CH_3CH_3} + \underset{\text{Ammonia}}{HNH_2} \rightleftarrows \underset{\text{Ethylamine}}{CH_3CH_2NH_2} + H_2$$

Ethylamine may be obtained indirectly from ethane by reacting the latter first with chlorine to form ethyl chloride and treating this reaction product with ammonia:

$$\underset{\text{Ethane}}{CH_3CH_3} \xrightarrow{Cl_2} \underset{\text{Ethyl chloride}}{CH_3CH_2Cl} \xrightarrow{NH_3} \underset{\text{Ethylamine}}{CH_3CH_2NH_2}$$

Thus we may consider the various types of organic compounds as derivatives or oxidation products of the hydrocarbons. Acetic acid, CH_3COOH, for example, is considered as an oxidation product of ethane:

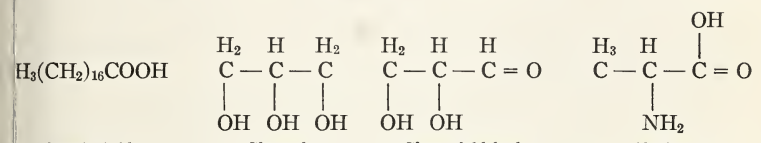
$$\underset{\text{Hydrocarbon}}{CH_3CH_3} \xrightarrow{[O]} \underset{\text{Alcohol}}{CH_3CH_2OH} \xrightarrow{[O]} \underset{\text{Aldehyde}}{CH_3CHO} \xrightarrow{[O]} \underset{\text{Acid}}{CH_3COOH}$$

Oxidation of the carboxylic acid takes place less readily than the previous oxidations; but with energetic oxidizing agents acetic acid gives carbon dioxide and an oxidation product of methane, thus resulting in a rupture of the carbon to carbon bond. In this manner it is possible to picture the

epwise degradation of higher or more complex carbon compounds to wer ones.

omplex Organic Compounds

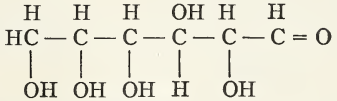
The more complex carbon compounds either have more carbon atoms their molecules than those which have thus far been considered or they ntain more than one functional group or both. For example, the follow- g four formulas represent complex carbon compounds. The compound



Stearic Acid — Glycerol (Trihydroxypropane) — Glycerylaldehyde — Alanine α-Aminopropionic acid

(1) (2) (3) (4)

presented by formula (1) is *stearic acid*, a carboxylic acid which may be nsidered as derived from the hydrocarbon octadecane, $CH_3(CH_2)_{16}CH_3$. ctually stearic acid is obtained from fats such as *tallow* in which stearic id is found as in combination with *glycerol* represented by formula (2). mparing formula (1) with formula (2) it will be noted that stearic acid is long chain carboxylic acid, while glycerol is a hydroxy derivative of opane, $CH_3CH_2CH_3$. Since glycerol has three hydroxyl groups it can called a trihydroxypropane, and hence it is an alcohol and will ex- bit all the properties of alcohols. For example, methane, CH_4, is in- luble in water, but its oxidation product methyl alcohol CH_3OH is very luble. Further methyl alcohol on oxidation gives an aldehyde. In the me manner glycerol is soluble in water and on oxidation gives an alde- de, glycerylaldehyde, shown in formula (3). This aldehyde contains o hydroxyl groups and one carbonyl and it is the simplest type of a *sugar*. he common sugar, glucose ($C_6H_{12}O_6$), can be written as having the fol- wing structure:



Glucose

(5)

om the structure it can be seen that like glycerylaldehyde, glucose is a ydroxyaldehyde. Finally, inspection of formula (4) shows that alanine und in the proteins in the human body is a simple *amino acid* derived om propionic acid, CH_3CH_2COOH, which in turn is an oxidation product

of propane. Amino acids are of importance because they are the buildin blocks of which proteins are built. From this very elementary discussio it is seen that the important types of compounds found in living tissue *carbohydrates*, *fats*, and *proteins*, are complex carbon compounds whic can be resolved to simpler structures. A number of these changes whic take place in the animal organism are discussed in the next chapter.

SUMMARY

1. The element carbon is the energy carrier of life. The changes involved in th processes of photosynthesis and respiration are essentially oxidation-redu tions of carbon atoms.
2. Photosynthesis occurs only in plants and involves absorption of energy ar partial reduction of carbon dioxide to organic compounds.
3. Respiration occurs in both plants and animals; it involves oxidation of o ganic compounds and transformation of the chemical potential energy heat.
4. Carbon is unique among the elements in that it forms a large number of con pounds containing many carbon atoms in the molecule. The carbon aton are assumed to be united with each other by sharing electrons forming lo chains or rings.
5. Carbon atoms have four valence electrons tetrahedrally arranged in spac diamonds and many carbon compounds have the tetrahedral structure, th is, a central carbon atom is at the center of the tetrahedron and four oth atoms or groups around it are at the apexes.
6. Isomers are compounds which have the same kind and the same number atoms in their molecules but have each a different arrangement of the vario atoms within the molecule.
7. Hydrocarbons contain only carbon and hydrogen atoms; all organic co pounds may be considered to be derived from the hydrocarbons by substit tion of other atoms or groups of atoms for one or more hydrogen atoms.
8. The simpler organic compounds are monohalogens, alcohols, amines, ald hydes, and acids; they may be formally regarded as oxidation products the hydrocarbons.
9. Functional groups are the reactive parts of a molecule which usually conf upon it its unique properties.
10. The structural theory of organic chemistry makes possible the systema study of carbon compounds.

STUDY EXERCISES

1. Trace the course of the element carbon from carbon dioxide as utilized photosynthesis and the respiration of animals, and show how it acts as t energy carrier in the living world.
2. Trace the course of atmospheric oxygen through the respiration of the anim and through the photosynthesis of plants.

. When either venous or arterial blood is subjected to a vacuum, a certain amount of oxygen and carbon dioxide is obtained. Discuss whether this indicates chemical combination of these two gases with components of the blood.

. For each of the substances in the following list give some information as to its chemical composition, symbol, or formula, if possible, and chief uses:

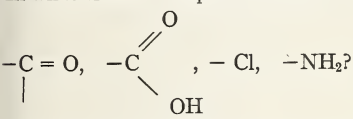
1. Diamond
2. Carbon dioxide
3. Graphite
4. Carbon monoxide
5. Methane
6. Butane
7. Ethyl alcohol
8. Formaldehyde
9. Acetic acid
10. Acetylene
11. Benzene
12. Ethylene
13. Methyl alcohol

. The elements found in carbon compounds are usually C, H, O, N, and the halogens. Thus carbon combined with a few elements forms nearly one million compounds, which is more than the number produced by all the other elements. To what principle is this attributed?

. In each of the following compounds write all the possible different arrangements of their atoms: C_4H_{10}; $C_4H_{10}O$.

. Using the tetrahedral model, show that there is only one compound having the molecular formula CH_2Cl_2. Assuming a planar structure, show how many isomers there might be.

. In what class of compounds is each of the following functional groups found:



. Compounds like ethylene, C_2H_4, exhibit many reactions which are not shown by ethane, C_2H_6. Explain this behavior.

. Natural gas boils from − 161° to + 1° C.; gasoline usually boils from 40° C. to 250° C.; paraffin melts at about 50–60° C. What information do these data give about the nature of the molecules of these mixtures of hydrocarbons?

. Explain the meaning of the following terms: photosynthesis; respiration; polymerization; saturated hydrocarbon; unsaturated hydrocarbon; amine; alcohol; carboxylic acid.

. Discuss some specific advantages that man has obtained through knowledge of carbon compounds.

. What are some of the distinctive properties of the element carbon as compared with the other elements?

FOR FURTHER READING

. Hatcher, W. H. *An Introduction to Chemical Science.*

For the general student, a good discussion of carbon will be found in Chapter 7, of carbon-oxygen cycle in Chapter 21, of the chemistry of living things, and of the chemistry of the simpler organic compounds in Chapters 23–27.

. Strong, Ralph K., *Chemistry for the Executive.*

A discussion of the simpler organic compounds will be found on pages 207–271.

3. Babor, J. A., *Basic College Chemistry.*
Photosynthesis is discussed on page 640, carbon and its oxides in Chapter 2 and organic compounds in Chapter 40.

4. Briscoe, H., *College Chemistry.*
Carbon and its oxides are discussed in Chapters 24 and 25, and organic compounds in Chapters 33 and 34.

5. Hildebrand, J. H., *Principles of Chemistry.*
Chapter 18 contains an excellent review of organic chemistry.

34

Sources of Energy

IE ENERGY OF LIFE was traced in the preceding chapter to its ultimate urce — the sun. The element of carbon was shown to be the vehicle in a iique and complex system of transportation by which the energy of the n is transformed into the energy of living cells. But, apart from the con-iuous consumption of food necessary to all animals, man is constantly eking large amounts of energy outside of his body. The energy require-ents in the United States are so enormous that all the hundred and forty illion people working together, aided by several million horses and other asts of burden, supply less than five per cent of the total. The remainder obtained from other than animal sources. Of these, coal, oil, and water-lls furnish the billions of horsepower that are required to keep our particu-type of civilization going. This fact is shown in Table 54, which lists e principal sources of energy available and the proportion of energy elded by each in the United States.

Inspection of the table indicates that the first five sources listed account r 95 per cent of the total energy used; they are all compounds of carbon. iother striking fact is that only foods and wood represent sources which e being produced at present, and that 91 per cent of the total energy re-

TABLE 54. SOURCES OF ENERGY

Source	Per Cent of the Total Annual Energy Utilized in the U.S.[1]
1. Coal and derived products	45
2. Oil (gasoline, kerosene, fuel oil)	33
3. Natural gas	13
4. Wood	1
5. Animal power (foods)	3
6. Alcohol (used for power)	*
7. Water power (falls and tides)	4
8. Wind	negligible
9. Internal heat of the earth	*
10. Direct heat from the sun	*
11. Nuclear energy	*

* Less than one per cent.
[1] Bureau of Mines and Census Bureau data for 1948.

quirements are drawn from coal, oil, and gas, which are accumulated ener reserves inherited from the past. At the present rate of consumption t question of how long coal and oil will last has a real significance.

As the present resources dwindle, future generations will turn the attention to other sources of energy. A few of the possible sources will considered briefly. The amount of solar energy accruing to the earth extremely vast; if all of it could be converted into power, it would furni 1.3×10^{14} horsepower. Our total requirements are but a very sma fraction of this figure. The harnessing of a part of the huge amount solar energy by mirrors or other devices has been proposed as a futu possibility.

The internal heat of the earth is another possible source of energy. obtain some of this heat it will be necessary to drill deep wells in order circulate water and thereby generate steam. This source is being utiliz at present on a very small scale in volcanic regions.

The force of the moving atmosphere has been extensively used in t past as a source of power for sailing ships and driving windmills. present, however, only a small amount of power is obtained from the win mills that stud the farms. Proposals, plans, and not a few experimen have been made to use the force of the wind to drive rotor towers in circul tracks and use them as electric generators; but as yet necessity has n forced the development of an economical method.

Finally, what are the prospects of utilizing atomic energy, for factor for home and farm? How soon can we expect to run our automobile railroads, surface ships, and airplanes by means of the "little nucle reactors"? These questions are a natural consequence of the wave optimism which follows the announcement of a great scientific discover The optimism which the people of this country felt was in a way justifi when one considers that, despite the spectacular aspects of nuclear energ which were publicized by the press, the fact remains that one pound uranium can be made to release an amount of energy equivalent to th released by 2,600,000 pounds of coal. The practical possibilities can realized further if the nuclear reactor is considered as a new type of "con pact storage battery." The ordinary automobile battery which delive six volts has an energy capacity of about one horsepower hour. A weig of uranium equal to that of the automobile battery would be capable delivering about 300,000,000 horsepower hours.

In order to obtain power from the release of nuclear energy it is necessa to construct a practical nuclear reactor which can furnish energy econom cally. A nuclear reactor is really a furnace in which nuclear fission is ca ried on at a controlled rate. In order to realize the technical problems th must be solved before any substantial part of our energy requiremen comes from nuclear energy, a brief summary will be given of the prese

atus of nuclear reactors from the most recent releases of the Atomic nergy Commission.[1]

The technical problems involved in the construction and operation of a uclear reactor are: (*a*) adequate supplies of fissionable material; (*b*) conruction materials for the reactor which are able to withstand the temratures, corrosion, and radiation density developed in its operation;) proper control of the reactor with particular concern for the safety of e operators; (*d*) operation of the reactor at high temperatures, as a condin necessary for efficiency; (*e*) the proper and safe disposal of the fission oducts. The problem of fissionable material is not insurmountable since ere are already three reactor fuels available: *uranium 235*, *plutonium*, d *uranium 233*. It was shown in Chapter 27 that uranium 235 is obined by isotope separation while plutonium 239 and uranium 233 are nthetic elements made from uranium 238 and thorium 232, respecvely.

The design and the selection of materials for the construction of the actor present a tremendous number of problems. The materials must be osen so that they can withstand high temperatures and concentration of netrating radiations. Aside from the corrosion effect, the properties of me metals undergo radical changes under high temperatures. The oblem is being studied through the construction of a "materials testg reactor." Another requirement is that the materials for reactor conruction do not readily absorb neutrons and thereby reduce their pply.

The energy produced in a nuclear reactor is due to the capture of neuons by the nuclei of fissionable elements which then become unstable and eak into fragments which are ejected with tremendous velocities; the utrons which are always released with the fragments may under proper re be utilized to produce other fissions. The energy developed in the uclear fission appears as an intense local heating of the fissionable maial. In the reactors which were built during the war the heat was moved by circulating large amounts of water, thus this "old type" of actor can furnish hot water which is not particularly useful for industrial eam generation or for conversion to electricity; for such purposes it is cessary to have higher temperatures, and to remove the heat by an effint heat transfer agent, as, for example, liquefied metals. At the present me the Atomic Energy Commission is actively engaged in the development of such a reactor. The Navy is developing a reactor to utilize turally occurring uranium enriched with uranium 235. A single charge

[1] *The Development of Nuclear Reactors*, by Robert F. Bacher, Member of United States Atomic nergy Commission, February 9, 1949; *The Utilization of Atomic Energy*, by Robert F. Bacher, arch 17, 1949; *Atomic Power and Its Implications for Aircraft Propulsion*, by Lawrence R. fstad, Director of Reactor Development, United States Atomic Energy Commission, July 22, 49; *Recent Scientific and Technical Developments in the Atomic Energy Program of the United tes*, United States Atomic Energy Commission, July, 1948.

of the reactor is expected to provide power to propel a ship tens of thou sands of miles.

The problem of disposal of the fission products so that the "ashes d not smother the fire" is a serious one inasmuch as the "ashes" are als highly radioactive and serve as a contaminant of the fissionable materia At the present time the unused fissionable material is removed an reclaimed for further use. The fission products are extracted, separated and stored for future use or disposal. They are really a troublesome by product which must be handled at considerable expense so as to protec people from the radiations.

Besides the materials testing reactor and the Navy reactor, two othe types are being built. One, called the experimental "breeder," is designe to operate with fast neutrons instead of the low energy neutrons used in th common types of reactor. The objective in the fast-neutron breeder is t destroy a smaller amount of fissionable material than that produced by th neutrons emitted in the fission process. In such a reactor it would be possi ble to extract and use energy from the fission process and to produce mor fissionable material than had been destroyed to obtain this energy.

The fourth type of reactor is designed to operate with neutrons of inter mediate energy capable of breeding new fissionable material and directe towards the production of electrical energy. This type, as well as the fas reactor, will have the heat removed by the circulation of a liquid meta thus providing a sufficient difference between two temperatures to operat an engine and convert heat to electrical energy efficiently. This reactor, i successful, will produce a significant amount of electric power and at th same time will demonstrate at least partial success in "breeding." A par of the complete program of reactor development is the exploration of th utilization of atomic power for aircraft propulsion.

Fuels

At present, however, as shown in Table 54, for about 95 per cent of ou energy requirements we depend on mixtures of carbon compounds: *food* and *fuels*. The advantages of liquid fuels are obvious: They are easier t transport, they are easier to burn, and there are no problems involving th disposal of ashes.

Fuels are substances that can be economically burned to produce hea energy for domestic or industrial purposes. This definition excludes man other substances which can undergo combustion, such as magnesium an aluminum; for, although they can furnish large amounts of heat, they can not be produced or utilized economically for domestic or industrial hea production. As previously pointed out, all fuels are compounds of carbo and hydrogen, and the products of combustion are carbon dioxide an water. Small amounts of other elements may be present, such as nitroge and sulfur, but the heat derived from their combustion is negligibl

evertheless, their products of combustion pollute the air and present a oblem in congested industrial districts like Chicago and Pittsburgh. his will be discussed later.

Fuels begin to burn at different temperatures; a lighted match near a ssel filled with gasoline is extremely dangerous, but a lighted match can extinguished by dipping it into lubricating oil. The latter can be burned ien heated to higher temperatures. The temperature at which burning gins is called the *kindling temperature.* Combustion, as previously noted, volves rapid oxidation and is accompanied by the familiar production of flame. As the solid or liquid fuel is heated, gases are produced which mix th the incoming air, and the chemical reaction of oxidation takes place the contact of the two gaseous mixtures, fuel and air, producing the aracteristic flame. In a candle flame, the heat melts the wax, which then cends the wick and produces gaseous hydrocarbons; these travel out- ards and in contact with the air begin to burn. Consequently, the hottest

TABLE 55. APPROXIMATE AMOUNT OF FUELS USED IN THE UNITED STATES

Name	Composition	Approximate Annual Production in Billions of Pounds	Value (Thousands of Dollars)
al.....	A complex mixture of organic compounds.....	1080[1]	3,870,000
ke.....	Mostly carbon with 6–10 per cent ash.....	148[2]	584,000
ood (fuel).....	Cellulose of plants.....	100[2]	165,000
troleum (crude).....	A mixture of hydrocarbons..	601[1]	5,210,000
soline (obtained from crude petroleum and natural gas).....	A mixture of hydrocarbons having 5–15 carbon atoms per molecule.....	260[1]	8,820,000
Name	**Composition**	**Billions of Cubic Feet**	**Value**
tural gas.....	Hydrocarbons with 1–4 carbon atoms (methane, CH_4, ethane, propane, butane..	4444[2]	534,400
anufactured gas	water gas, coal gas, oil gas, producer gas, blast furnace gas	524[2]	451,300

[1] Estimates based on production during 1948.
[2] Estimates based on production during 1947.

part of a candle or gas-burner flame is the outer surface of the cone, wh the coldest part is the inner core of the cone, as can be shown by holdin match across a small flame; the wood in the middle remains uncharr When the supply of air within the inner core is not abundant, as in a can flame, the reaction proceeds slowly; some carbon is produced, which is th heated to high temperature and glows, becoming manifest as a *lumino* flame. When air is premixed with the gas, as in the kitchen burner, t flame is smaller, hotter, and *non-luminous*. The temperature attain depends on the type of burner and the nature of the fuel. With a Buns burner, a copper wire can be melted — this requires about 1083° C. a gasoline blow-torch flame, the temperature is about 1500°; in the ox hydrogen flame, about 2000°; in the oxyacetylene, 2400° C. The chemic reactions taking place at the border of the flame are complicated and ne not be discussed here.

For convenience, fuels are usually grouped according to their physic state: solid, liquid, and gaseous. Table 55 exhibits such an arrangemen For the present, however, fuels will be discussed under the heads of Co and Petroleum.

Coal

Coal is a compact mass of the remains of plant tissues altered and co solidated (metamorphosed) as a result of being buried under the crust of t earth. It usually occurs in beds alternating with beds of clay or shal Both in the coal seams and in the adjoining clay beds, impressions of leav roots, and even stumps of trees are found, offering evidence of the natu and mode of formation of coal. Most coal shows a tendency under the i pact of a hammer to break into small blocks or very small particles a proaching dust. When examined closely, most pieces of soft coal sh divisional planes indicating the effect of pressure.

As is well known, when wood decays, exposed in the atmosphere, it slowly decomposed by fungi and bacterial ferments and apparently di appears. A decomposing log or branch is a familiar sight in the woo But when wood undergoes decay submerged in water, as in swampy r gions, with the air partly excluded, it is slowly changed to a brown, past compact mass known as *peat*. The changes are brought about by ba terial ferments, and during this process there is a progressive loss of oxyg and hydrogen, with the production of water, carbon dioxide, and metha (CH_4); the latter is commonly called "marsh gas" from this mode of pr duction in nature. When peat is buried deep, it is slowly changed to a lo grade coal called *lignite*. The changes are brought about by geologic caus and are similar to the processes by which sediments are changed into rock When peat changes to lignite, there is an increase in the percentage of ca bon. If subjected to increased pressure by being more deeply buri lignite is changed to *bituminous* coal. It is understood that this mode

Table 56. Composition of Different Kinds of Fuels

Sample	Water	Volatile Matter	Carbon	Ash	Approximate Composition of Dried Samples Excluding Water and Ash			Heat Value (B.T.U. per lb.)
					Carbon	Hydrogen	Oxygen	
ood.....	11.5	....	....	0.3	50.0	6.0	44.0	4,500
at.....	15.0	50.00	25.0	10.0	59.0	5.0	36.0	4,500
gnite.....	32.0	30.0	29.0	9.0	67.0	6.0	27.0	6,500
tuminous coal...	4.0	35.0	53.0	8.0	80.0	5.0	15.0	14,000
nthracite.....	3.3	3.0	91.0	2.7	95.0	2.5	2.5	15,500

rmation is hypothetical; lignite and bituminous coal are classified on the sis of their chemical and physical characteristics, and these are assumed have resulted from different conditions to which the plant débris has en subjected. Reference to Table 56, which lists analyses of different nds of coal, shows that lignite and bituminous coal have a high percentge of volatile matter — that is, when these coals are heated, from 30 to per cent of the weight of the coal is given off as a black, smoky, gaseous ixture. The amount of carbon increases from about 30 per cent in gnite to 50 per cent in bituminous coal. At the same time there is a dease of oxygen from about 27 per cent in lignite to 15 per cent in bitumius coal. From these data, and in addition the physical characteristics d the nature of the strata in which these coals are found, the conclusion drawn that lignites are young coals, while the bituminous are more ma-re. The last stage in coals is reached in *anthracite*. This is a hard coal thout the cross-jointing structure characteristic of lignite and bitumius coal, having very little volatile matter and a high percentage of fixed rbon. It is assumed that anthracite has resulted from bituminous strata hich have been repeatedly folded and squeezed. In the foothills of the ppalachian region in Ohio the coal-bearing strata are horizontal, and the al is more closely related to that found in Illinois than to the beds a little the east in Pennsylvania, where the coal beds found in the mountainous gions are highly folded and consist almost entirely of anthracite.

The coal found in the Illinois, Kentucky, and Pennsylvania regions was rmed prior to the elevation of the Appalachian Mountains during the ter part of the Paleozoic Era. The conditions during the geologic periods extensive coal-making swamps must have been warm, moist climate, xuriant forest growth in swampy lowlands along rivers, and a relatively stable continent. As the continent subsided, the plant material that d accumulated in swamps was buried by sediments of sand and mud ay). When the region was re-elevated, a new forest grew on these sedients, which after an interval of several thousand years were again covd by mud and clay. In this manner the alternating strata of coal and ale came into existence. Occasionally the subsidence was extensive, and

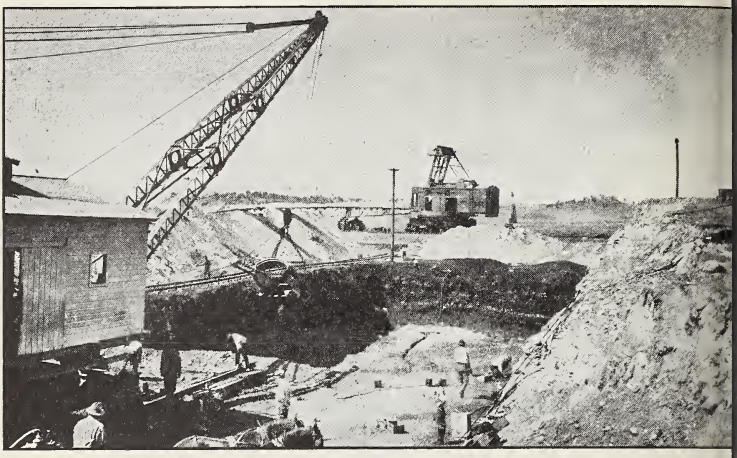


FIGURE 313

STRIP PIT ON THE ROSEBUD COAL BED AT COLSTRIP, MONTANA
(*Courtesy of U.S. Geological Survey*)

the region was covered by shallow seas with a deposition of limeston Figure 313 shows a typical coal bed.

Petroleum

Petroleum, or rock oil, was known to the ancients through pools th formed at the earth's surface; it was used for illuminating purposes in t same manner as it was used here prior to the development of the autom bile. Petroleum was discovered in America in 1627 but was first produc on a commercial scale in 1859. The first oil well was drilled at Titusvil Pennsylvania. In the short time of ninety years petroleum has altered n only the civilization of the United States but also the civilization of a lar part of the world. The internal combustion engines of the automobile a the airplane were made possible only through the mixture of hydrocarbo known as *gasoline* and *lubricating oil*, derived from the dark, viscous liqu which is obtained from the crust of the earth. The world's production crude oil in 1945 was over 684 billion pounds, of which 70 per cent w produced in the United States.

The modern view of the origin of petroleum is the result of consideri the type of rocks in which it is found and traces of compounds which it co tains; it is always found in beds which have marine strata, never in igneo rocks; it contains, in small amounts, derivatives of chlorophyll, haemi and hormones, all of which are unquestionably of organic origin. Petr leum, therefore, is assumed to be formed in muds, clays, and shales fro

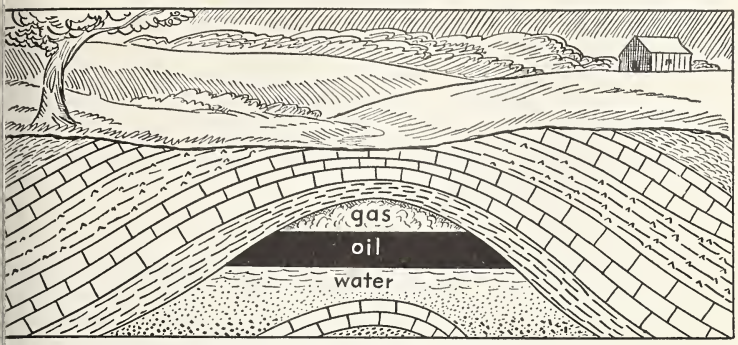


FIGURE 314. ANTICLINICAL OIL-BEARING STRATA

The gas, being the lightest, occupies the top of the fold; the oil is below the gas; finally the water, the heaviest of all, is at the bottom.

e decomposition of animal and vegetable matter. The products, together ith gas and salt water, diffuse into porous sandstones and limestones. order for petroleum to be obtained from oil-bearing strata, a natural paration must have taken place through faulting or folding. In other ords, geologic changes in the region have caused the gas to migrate to the p of the fold with the oil below it, and finally with the water at the lower vel. For example, Chicago is built upon a deposit of limestone which ntains for each square mile 7,500,000 barrels of oil, but which cannot be covered, as it is not accumulated in pools or pockets. If this region had dergone diastrophic movements, the oil would have collected in the per part of the anticlinical folds. The wells are drilled after geological udies, so that the wells top the upper part of the folds. The chief oil-

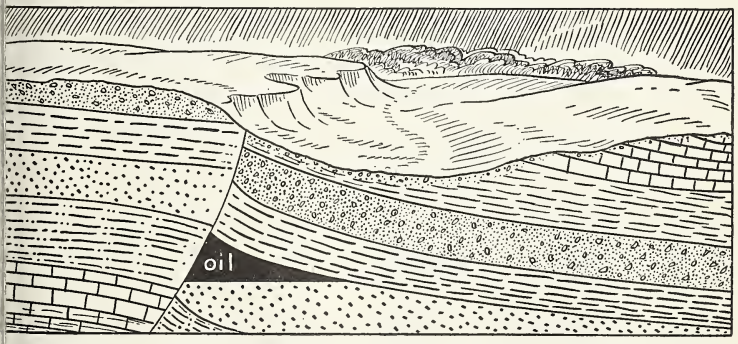


FIGURE 315. A RESERVOIR FORMED BY FAULTING

An impervious layer overlies the reservoir stratum and holds the oil in the structural trap formed by the fault.

producing regions of the United States are in Pennsylvania, Ohio, Okl homa, the Gulf Coast region, the Northwest (Wyoming and Montana and the California regions. Most of the United States oil fields are i older formations — that is, Paleozoic and Mesozoic rocks — whereas mos of the other great oil fields of the world, in Baku, Rumania, and Burm are in rock formation of more recent origin (Cenozoic). The compositio of crude oils varies with their sources.

Refining of Petroleum

Petroleum as obtained from the ground is a viscous liquid with a greenis fluorescence. The color ranges from pale yellow to black. Crude petr leum must be refined, for it cannot be used as a motor fuel or an illuminan because of its many impurities. The refining of petroleum is accomplishe by fractional distillation and subsequent chemical purification of the dis tillate. By fractional distillation is meant the separation of a liquid mix ture into several portions by distilling and collecting different fractions a the temperature rises. The composition of the fractions depends largel on the origin of the crude oil. In general practice the fractions indicate as I and II in Table 57 are separated; the constituents of gasoline boil o first, then kerosene. After removal of these two fractions the distillatio may be discontinued at this point and the remaining crude oil (toppe crude) utilized as *fuel oil* in industrial and domestic heating. The distill tion may be continued, however, to obtain fractions III and IV; the lubr cating oils are used to minimize resistance between the moving metalli parts of a machine. After distillation and upon cooling the oils deposit solid which is known as *paraffin*. Certain types of lubricating oils are de colorized by careful treatment with sulfuric acid, fuller's earth, decolorizin carbon, or other agents to a water-white liquid known as *mineral oil.* I is used extensively for the preparation of cosmetic "cold cream," and as laxative in medicine. Another product of the refining of petroleum petroleum jelly, or vaseline, a white, butterlike mass used in the prepara tion of ointments. Vaseline consists mainly of paraffin hydrocarbons.

TABLE 57. PRIMARY DISTILLATION OF CRUDE PETROLEUM

Fraction	Name	Boiling Range C.°	Composition [1]	Yield % [2]	Uses
I	Gasoline	35–225	6–10	25	Motor fuel
II	Kerosene	225–300	10–12	12	Fuel
III	Gas oil	300–400	10–14	37	"Cracked" Gasoline [3]
IV	Lubricating oils	400–450	12–16	7	Lubricants
V	Residue	....	14 and above	19	"Cracking" operations

[1] Number of carbon atoms in the hydrocarbon molecules found in the fraction.
[2] Average yield based on the volume of crude oil used in the distillation.
[3] This may be refractionated to obtain various solvents, used for paints and the like.

Cracking. Reference to Table 57 shows that fractions III and V add up more than 50 per cent of the original crude oil. The combined fractions I and V are used to produce more gasoline. The fundamental difference etween the gasoline fraction (I), for which there is a large demand, and ie higher boiling fractions is that the constituents of the latter have larger olecular weights, that is, they have more carbon and hydrogen atoms per olecule. Therefore, to convert these high-boiling fractions into gasoline is necessary to "break-down" the molecules of high molecular weight to olecules of lower molecular weight. In the older processes the high boil- g fractions were subjected under pressure to temperatures above those nployed in ordinary distillation of petroleum. Under these conditions drocarbons of high molecular weight underwent rupture or *cracking* to naller molecular fragments similar to those which occur in gasoline. In e modern processes, the cracking is accomplished catalytically. The ude oil is vaporized and preheated and is then blown through a bed of ely divided solid catalyst at a rate so controlled that each particle of the talyst is surrounded by the vapors of the crude oil. The bed of the solid talyst thus becomes a "mobile fluid" and boils off like a liquid. This luidized" action greatly promotes the "thermal cracking" of the crude into low molecular weight compounds or "cracked gasoline."

In the cracking operations, besides the low molecular weight saturated drocarbons which are used as gasoline there is always produced in addi- n to hydrogen a considerable amount of *unsaturated* hydrocarbons of w molecular weight. These must be removed from the cracked gasoline ce their presence leads to gum formation in the gasoline lines and ori- es of the motor car and to increased vaporization losses. In the early ys of the petroleum industry the unsaturated hydrocarbons were utilized fuel in the distillation of petroleum. Today they are utilized to produce nthetic gasoline, synthetic rubber, and a variety of plastics. In the oduction of synthetic gasoline the molecules of the unsaturated hydro- rbons are made to react with each other or add to each other to form ger molecules; this process of addition of similar molecules to form larger lecules is called "polymerization." In the production of synthetic soline the conditions must be chosen so as to avoid the formation of ge molecules (as in the production of synthetic rubber and plastics). e temperature and catalysts are so chosen that molecules having 6 to 8 rbon atoms are formed almost exclusively. By this and other methods e amount of gasoline from crude oil has been raised from 25 per cent ob- ned by simple distillation to a total of 60 to 70 per cent of the total lume of the crude petroleum.

The demand for gasoline and other motor fuels all over the world has creased tremendously during the past 25 years. This can be realized by nsidering the daily production of crude oil; twenty-five years ago 80 llion gallons of oil were produced daily, whereas today the figure is close

to 350 million gallons. The increased demand for liquid fuels and th diminishing reserves led to serious planning and research for new source Three general methods are presently being explored both by governmenta agencies, such as the Bureau of Mines, and by private industry. One ap proach is to liquefy low grade coals, such as lignite, by combining the finel pulverized coal with hydrogen under pressure. This process (Bergiu process) has been used in Germany since 1923 and was producing in 193 about 100 million gallons of liquid fuel per year. The second approach i to extract oil from shale. It has been estimated that it is possible to ex tract from shale in the United States many millions of gallons annuall The third approach, which is being very intensively investigated and d veloped, is the production of liquid fuels from natural gas or from a mixtu of carbon monoxide and hydrogen (water gas) formed by passing stea over hot coal. This gas synthesis of liquid fuels, called the *Fischer-Tropsc process*, was developed in Germany between 1923 and 1930. Intensiv work in this country began about ten years ago and at present is near t commercial scale production in economic competition with crude oil as source of liquid fuels.

Conservation of Fuels

It has been estimated by the United States Geological Survey that ther are available in this country about twenty-five hundred billion tons c accessible coal, not including lignite. If the present rate of consumption c six hundred million tons per year is continued, this coal supply should las about four thousand years. Although this figure is so large that it may nc appear to be a concern to the present generation, the estimate for the o reserves brings the problem of conservation close to the present scen According to present estimates, the known supplies of crude oil in th United States will last from seventy-five to one hundred years. The att tude of the optimists is that man's ingenuity will rise to the occasion an solve the problem of the dwindling supply. Very definitely the directio of development is towards synthetic fuels, using cheap, low-grade coal However, the problem of conservation is a serious one, for sooner or lat future generations will be called upon to "live within their income. Practically 91 per cent of our energy sources are drawn from accumulate reserves of the past, and consequently this "savings balance," since receives but infinitesimal deposits, will dwindle to zero.

The Smoke and Soot Evil

The use of coal and gasoline in industrial centers and congested metr politan districts presents some very serious problems to the health of th inhabitants, who breathe air polluted with soot, smoke, and the exhau gases of automobiles. The extent of pollution may be realized from th estimates on the amount of soot deposited annually in large cities. Th

nual deposit of soot in the city of London is fifty-five thousand tons. e cannot put all the blame on the railroads and factories, for, according the report of the special commission of the Chicago Association of Com- erce, the furnaces of apartments and homes produce 57 per cent of all e soot and tarry products discharged into the atmosphere of Chicago. ne exhaust gases of the automobiles, particularly in congested streets over nich there is a continuous stream of traffic, aggravate the situation. In dition to carbon monoxide and products of incomplete combustion, ere are small amounts of lead salts from the tetraethyl lead in the anti- nock gasoline. Although some authorities claim that the small amounts lead thrown out in the exhaust gases can be eliminated by the body, still ere is a question as to whether the organism of the city-dweller should be rdened further. Our advances in industrial civilization are thus usually companied by a multiplication of problems both economic and hy- enic. These problems are usually not properly recognized in the ginning. There is too much enthusiasm for the "bigger and better" and o much emphasis on the dollars saved or gained, an attitude which pre- nts a cool and impartial examination of all the advantages and disad- ntages resulting from the application of a new technological discovery. ne hygienic and social consequences of any technological development ould be of greater importance than profits and expediency.

nsumer Aspect of Fuels

The student is referred to the section on machines at the end of Chapter . In discussing the efficiency of machines, the common sources of energy re listed in the order of increasing cost per unit of energy. It will be ll, now that a more detailed discussion of the sources of energy has been en, to consider this matter again, particularly from the point of view of e consumer. The two factors of primary importance to the consumer are *t* and *efficiency*. The matter of cost can be approached by considering e comparative cost of 100,000 B.T.U.'s of energy (1 therm) from various rces. Table 58 lists the approximate cost which the consumer pays in taining this amount of energy. The figures therein, however, are apt to misleading. Although the cost of one therm of energy from coal is five nts and from artificial gas is nineteen cents, this does not represent the ual cost. The use of coal entails work: starting the fire, shoveling coal m time to time, and removing the ashes. The cost of this work must be luded in order to obtain the actual cost. The use of gas has the advan- e that it is easy to transport to the point of use and that there are no id waste products to dispose of after burning.

Another factor that enters into the choice of a fuel is the efficiency of its lization. In the ironing of a shirt, for example, coal may be used, as it was rty-five years ago. A solid iron was placed on a grate above coal and ted, then removed and cleaned with a rag, and then applied to the shirt.

TABLE 58. APPROXIMATE COST OF ENERGY FROM VARIOUS SOURCES

Source	B.T.U.	Approximate Cost * per 100,000 B.T.U.
Sunlight	———	$0.00
Coal	13,200 per lb	0.05
Natural gas	1075 per cu ft	0.12
Fuel oil	19,000 per lb	0.14
Gasoline	20,000 per lb	0.17
Manufactured gas	600–900 per cu ft	0.19
Electricity	7000 per kw hr[1]	0.57

*Based on estimates of prices at New York and Chicago, October, 1949.
[1] At 4 cents/kw hr.

This operation today is performed with an electrically heated iron. Hea produced by electrical means costs about ten times more than coal hea However, the heat produced by electrical means is utilized to the exte of 90 to 100 per cent, while in the case of coal most of the heat is los Consequently, the heat produced electrically, aside from the convenienc is almost as economical as that produced by coal. The initial cost of co is comparatively so small that despite its many disadvantages it is st used as a source of about 45 per cent of the total energy utilized in th United States. Therefore it is advisable to consider some of the pertine facts for the consumer who buys coal.

To buy any goods intelligently, two standards are required: one fo quantity (weight, measure, and so forth) and the other for quality (grade There are definite standards for quantity for almost everything. Th housewife can check the weight of meat or the volume of milk and likewis (if it becomes necessary) the weight of so many bags of coal. There ar only a few articles for which rough standards of quality exist — amon them milk and meat. But for coal the average consumer has no criterio except fancy names such as "extra-fine," "Hades-hot," "Sure-fire," o "Sahara coal." The scientific method of buying coal used by consume who utilize large quantities may be briefly outlined. The percentage o water (moisture) is determined by accurately weighing a sample and hea ing it at 100° C. until the weight is constant. High moisture, of course, undesirable, for aside from the fact that the consumer pays for the wate heat is wasted in evaporating the water and sending it up the chimne The amount of ash is determined by burning the dried sample of coal unt the weight is constant. Soft coal may contain from 10 to 20 per cent o ash and moisture. Coal with 20 per cent of ash and moisture at $9 p ton costs 38 cents more per ton than coal with 8 per cent ash and moistu at $10 per ton. The heat value of coal is then determined by burning weighed amount in a calorimeter. The B.T.U.'s per pound may va from 6500 to 15,000. With this information it is possible for the consum to form a scientific basis for the price. For example, if the coal contai 4 per cent moisture and 6 per cent ash, this is deducted from the weigh

the coal yields 14,000 B.T.U.'s per pound this figure is multiplied by the
:t weight of coal, and the consumer can buy at so much per 100,000
.T.U.'s.

The above method cannot be used by the small consumer who uses only
ve to fifteen tons of coal per year. Further, the home owner must con-
der such factors as size, softness (whether the coal breaks too easily), and
olatility; the latter term indicates the amount of gas and smoke given off
hen the coal is burning. For this reason the Federal Consumers' Coun-
l is advocating the proper classification of coal according to its usefulness
to grades A, B, C, and the like. Thus a coal rated "A" for the B.T.U.'s
id "B" for ash will correspond to definite values, and the consumer will
e able to buy intelligently. It is hoped that with the education of the
onsumer such a procedure will be speedily adopted.

oods

Foods are mixtures of (*a*) compounds of carbon, (*b*) water, (*c*) small
nounts of inorganic salts usually called minerals. The amount of water
foods can be found by ascertaining the loss in weight which a sample
ndergoes when heated for several hours at 100° C. The amount of heat
hich a unit weight of food can produce in the animal body is ascertained
y determining the number of calories produced by the complete combus-
on of a certain weight of dry (dehydrated) sample. The amount of ash
hich remains on complete combustion gives information as to ratio of
organic salts present in the sample.

Table 59 lists a number of common foods. Inspection of the table shows
at the ash is a very small component, while water makes a very large
art of the total. The more abundant compounds of carbon found in
ods are classified into three groups: *carbohydrates*, *fats*, and *proteins*. In
ddition to the components shown in the table, it has been demonstrated
at foods contain small amounts of organic compounds which are neces-
ary for the normal development and functioning of the body and which
e called *vitamins*. Therefore, the essential nutritive requirements are:
ater, *salts* (or *minerals*), *carbohydrates*, *fats*, *proteins*, and *vitamins*.

The average assortment of foods which a family uses over a period of
me is called the diet. The present American diet is not entirely guided
y scientific knowledge of essential nutritive requirements, although it
ows trends in that direction. Like diets in other countries, it follows
e rules of tradition and experience of past generations. This experience,
owever, was not planned or examined critically with reference to the
est nutritive foods. Tastes, appetites, fads, whims, fancies, geography
availability of foods), and some experience based upon observations were
ll factors that entered into the development of the traditional diets that
ere handed down from generation to generation until the beginning of
he present century. About this time, a newer knowledge of nutrition

based on essential requirements began to develop, and this today promis to supplement and correct the traditional diet and thus afford a sou guide for the life of the individual. Through this knowledge we are able understand how foods are utilized in the body, what foods are essential, a how to remedy the deficiencies of certain diets. In this manner, t informed individual of the American community is able today even with small income to select and prepare the proper foodstuffs for a healthf diet. The newer science of nutrition is rapidly becoming a guide for fo production and distribution.

Table 59. Average Composition of Some Foods

Food	Water %	Protein %	Fat %	Carbohydrates %	Refuse %	Ash %	Calories per poun
Beef							
shoulder	57.9	16.0	10.1	0	15.2	0.8	735
flank	56.1	18.6	19.0	0	5.5	0.8	1185
heart	53.5	14.8	24.7	0	5.9	0.9	1320
Bacon							
smoked	10.4	9.5	66.9	0	8.7	4.5	2685
Chicken							
broiler	43.7	12.8	1.4	0	41.4	0.7	295
Fish							
mackerel							
edible portion	73.4	18.3	7.1	0	..	1.2	645
Eggs							
boiled	67.5	14.5	16.6	0.5	..	0.9	975
Butter	11.0	1.0	85.0	0	..	3.0	3605
Cheese							
American	31.6	28.8	35.9	0.3	..	3.4	2055
Milk							
whole	87.0	3.3	4.0	5.0	..	0.7	325
Oleomargarine	9.5	1.2	83.0	0.0	..	6.3	3525
Corn meal	12.5	9.2	1.9	75.4	..	1.0	1655
Rolled oats	7.7	16.7	7.3	66.2	..	2.1	1850
Wheat flour	11.4	13.8	1.9	71.9	..	1.0	1675
Bread							
whole wheat	38.4	8.7	0.9	49.7	..	1.3	1140
Rice	12.3	8.0	0.3	79.0	..	0.4	1630
Asparagus							
fresh	94.0	1.8	0.2	3.3	..	0.7	105
Cabbage							
fresh	91.5	1.6	0.3	5.6	..	1.0	145
Cucumber	95.4	0.8	0.2	3.1	..	0.5	80
Peas							
dried	9.5	24.6	1.0	62.0	..	2.9	1655
Potatoes							
boiled	75.5	2.5	0.1	20.9	..	1.0	440
Apples							
edible portion	84.6	0.4	0.5	14.1	..	0.4	290
Oranges							
edible portion	86.9	0.8	0.2	11.6	..	0.5	240
Peanuts							
edible portion	9.2	25.8	38.6	24.4	..	2.0	2560

The preceding paragraph should not give the impression that we are ıperior to past generations of men. But we have the knowledge needed)r the possibility of a superior development. It must be remembered ıat the science of nutrition could not develop until chemical and physi-logical studies regarding the nature of foods and their utilization in the)dy had made considerable progress. The progress made during the past fty years over the progress made during the previous five thousand years lustrates the difference between the empirical and the scientific method. mpirically, man had discovered, long before vitamins were recognized, ıat various fruits, herbs, and roots were likely to prevent certain diseases ıd to cure others. Some of this empirical knowledge is apt to be regarded y the enthusiastic neophytes of modern science as superstition. For :ample, the administration of the ashes of burned sponges for goiter may e regarded as superstition until it is shown that these contain iodine, remedy for certain types of goiter.

arbohydrates

Carbohydrates make up more than half of the average diet. They in-ude sugars, starches, and the indigestible fibers or celluloses from plants. he sugars and starches serve essentially as fuels. The sugars are sweet ystalline substances which are widely distributed in nature, particularly fruits and vegetables. Glucose, or dextrose, occurs in the juice of grapes ıd other fruits and is probably the most important *simple* sugar. Other mple sugars are fructose (fruit sugar) which occurs in honey and fruits, ıd galactose which results when lactose (milk sugar) is hydrolyzed. The ıemical composition of these three simple sugars is expressed by the for-ula $C_6H_{12}O_6$. They have the same number and kind of atoms but a ghtly different arrangement of the various groupings. The most impor-nt groups in the molecule of sugars are the alcohol group (OH) and e carbonyl group (CO). It is by virtue of these groupings that sugars ıdergo complex reactions. For example, a molecule of glucose and one fructose combine to form a molecule of a more complex sugar, sucrose ane sugar or beet sugar, which are identical). This is inferred from the ct that when sucrose is heated with acidified water or treated with saliva breaks down into a molecule of glucose and a molecule of fructose:

$$\underset{\text{Sucrose}}{C_{12}H_{22}O_{11}} + H_2O \xrightleftharpoons[\text{or enzymes}]{\text{HCl}} \underset{\text{Glucose}}{C_6H_{12}O_6} + \underset{\text{Fructose}}{C_6H_{12}O_6}$$

herefore sucrose results from the combination of two simple sugars, glu-se and fructose, and the elimination of a molecule of water. Glucose ıd galactose unite in a similar manner to form lactose, or milk sugar, ıich is found to the extent of from three to five per cent in the milk of ammals.

The complex carbohydrates are built up by the union of simple sug molecules, in a manner analogous to that in which cane and milk sugar a built up. For example, all the starches found in corn, wheat, rice, an potatoes are built up of glucose units. Thus, the molecule of starch is b lieved to be built up of twenty-five to thirty glucose units; this would assig a molecular weight of about 5000 to starch, the molecular weight of gluco being 180. With an increase in the size of the molecule there is a decrea in the solubility and reactivity. Starch is not soluble but forms a di persion in water, and does not react with the same ease as the simp sugars. Observations during the growth or synthetic processes of plan show that during photosynthesis simple sugars are first formed from carbo dioxide and water; these are circulated through the sap in the various par of the plant to build tissues, and the excess is transformed into starch. small part of the starch remains in the leaves, but the larger part is store in the reservoir of the plants, the seeds, tubers, and rhizomes. As nece sity arises, the starch is depolymerized to simple sugars and utilized f energy required in the vital functions. Thus, the system "simple suga $\rightleftarrows$ starch" is the method utilized by nature in protecting a reacti molecule. It is polymerized into a large molecule, relatively inert, leaving small amount of the reactive simple sugar available, which can be co stantly replenished from the reservoir by depolymerization:

$$\underset{\text{Starch}}{(C_6H_{10}O_5)_n} + nH_2O \rightleftarrows \underset{\text{Glucose}}{nC_6H_{12}O_6}$$

In the animal body the starches and complex sugars are converted by t enzymes of the digestive juices to simple sugars such as glucose. T process is essentially hydrolysis; as shown in the equation above, hydr ysis is a reaction in which water reacts chemically with a substance. T simple sugars are absorbed through the intestinal wall into the lymph a blood stream. In the muscles and liver the simple sugars are polymeriz to animal starch or glycogen, leaving in the blood stream 0.1 per cent glucose. Whenever the body needs more glucose for fuel, it is drawn fro the glycogen in storage.

Another complex carbohydrate is cellulose. Like starch, it is built glucose units, and hence its formula is given as $(C_6H_{10}O_5)_n$. Cotton co tains about 90 per cent of pure cellulose. It is insoluble in water and a other common solvents. When boiled for a long time in an acid solutio it is converted into glucose. The cellulose molecule is assumed to be ma up of about a hundred glucose units joined through oxygen atoms. The cellulose units are called *micelles*, and a large number of micelles arrang in parallel constitute the cellulose fiber. The parallel arrangement of the molecular units is assumed to give the strength characteristic of cott and other cellulose fibers. Cellulose is a more complex and, hence, a mo resistant molecule than starch. It is used for protection of the plant ce

ıd makes up the larger part of the woody plant fibers. It is broken down glucose with difficulty. In man, cellulose fibers are not digested, but rve by their bulk and water-holding properties to promote the progress food in the intestines and the evacuation of undigested matter. In the testines of certain animals (herbivores) there are enzymes present which n digest cellulose; hence, straw and hay form an important part of animal ods. Man, however, by processing and slightly changing the cellulose olecule, has been able to derive some important uses from woody fibers her than cotton. Paper and rayon are examples.

ıts

Fats are compounds that result from the union of complex organic acids ith the alcohol glycerol. The student should review page 613. Fats are :amples of *esters*. Under various circumstances, fats will react with ater, a process called hydrolysis, to re-form the organic acid and alcohol. ı this manner, in animal digestion, the fats are broken down by digestive ızymes to glycerol and organic acids; and after absorption through the testinal wall the fragments are resynthesized into the fats which are ıaracteristic of each animal. A small amount of fat is left in the blood, ıd the rest is stored under the skin and around many organs.

Animal fats, such as butter and tallow, usually have a solid or semi-solid ınsistency at room temperature. The fats from plants are usually liquid ıd are called *vegetable oils*. Most of the organic acids from animal fats e saturated molecules; in other words, they do not exhibit reactions ıaracteristic of the unsaturated hydrocarbon ethylene ($CH_2 = CH_2$). n the other hand, many vegetable oils contain a considerable amount of e esters of unsaturated acids. Consider, for example, stearic and oleic ids:

$$\underset{\text{Stearic acid}}{CH_3(CH_2)_{16}COOH} \underset{+H_2}{\overset{-H_2}{\rightleftharpoons}} \underset{\text{Oleic acid}}{CH_3(CH_2)_7CH = CH(CH_2)_7COOH}$$

$C_{18}H_{36}O_2$ $C_{18}H_{34}O_2$

s shown by the formulas, they differ by two hydrogen atoms; in other ords, stearic acid is a saturated molecule, but oleic acid is an unsaturated olecule. Under appropriate conditions, oleic acid can be made to react ith hydrogen and is thereby converted to stearic acid. In this manner, e vegetable oils — olive oil and cottonseed oil, which contain a con- derable amount of unsaturated acid, can be *hydrogenated* to give animal- ke solid fats ("Crisco," "Spry," and so on). On the other hand, vegetable ls like linseed oil and chinawood oil, which contain acids with an even eater degree of unsaturation, are very reactive. Under the influence of talysts, when exposed to air in the form of a thin film, they undergo ıidation and then polymerization, resulting in a tough, rubbery sub-

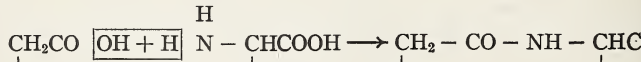
stance impervious to water. This property forms the basis of paint Paints usually consist of a vegetable oil like linseed oil, a small amount some catalyst (dryer), and a pigment.

In the animal body, fats serve primarily as fuels. Like the carboh drates, they undergo enzymatic oxidation to give carbon dioxide, water, an heat. The first stage in the oxidation of fats seems to be dehydrogenatic and the production of unsaturated compounds that are more reactiv Besides being important sources of energy, fats have other functions: the are necessary constituents of the tissues of the body and also act as regulato of food intake. This regulatory function depends on the slow rate of dige tion of fats as compared with that of carbohydrates and proteins. Since the digest slowly, fats delay the sensation of hunger. Low fat content in th food causes an abnormal feeling of hunger a few hours after meals. Finall fats are necessary for the absorption of certain vitamins (A, D, E, K).

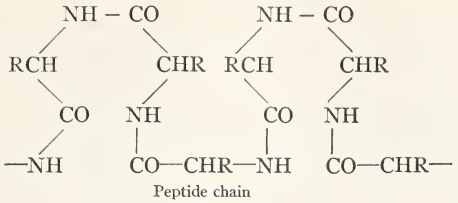
Proteins

Proteins serve as the essential parts of the animal engine in which ca bohydrates and fats burn; they are the basic constituents of all tissue perform and coordinate the functions of the body, and transmit heredity hence, proteins are considered to form the basis of life.

The number of proteins is very large; among the most common a casein from milk and albumen from eggs or blood. Proteins differ fro carbohydrates and fats in that they contain nitrogen (16 to 17 per cent besides carbon, hydrogen, and oxygen. As mentioned at the end of Cha ter 33 (page 614), proteins have a very complex structure; their molecul weight, which varies between 36,000 and 5,000,000, gives an idea of th complexity of their structure. It is also true that on digestion, eith with enzymes or dilute acids, proteins are broken to smaller fragmen called *amino acids*. About thirty different amino acids have been obtaine from proteins; it is assumed that the amino acids combine with each oth to form the proteins, which in turn combine to form tissues. The unio of amino acids, which may be likened to the union of the letters of th alphabet to form words, is assumed to take place through the amino a carboxyl groups, which are present in every amino acid. For exampl two amino acids may combine as follows:



The product of this chemical union is called a *peptide*. By the union many amino acids through combination of the carboxyl group of one wi the amino group of another, a large molecule of the resulting protein formed. The peptide is assumed to be arranged in loops as follows:



Peptide chain

In the digestive tract, through the action of several kinds of enzymes, roteins are hydrolyzed to amino acids which pass through the intestinal all to the lymph and blood. From the circulating blood, each cell selects nd removes the amino acids it needs to build up its particular proteins. he amino acids which are not required for tissue-building are broken own by the cells and utilized as energy sources. The human body is able synthesize some of the amino acids but not all. Obviously, those that nnot be manufactured must be obtained from food. It is therefore im- ortant that the diet should include proteins which contain these essential mino acids. A variety of both meat and vegetable proteins in the diet sures a supply of the required amino acids. Deficiency in the required mino acids leads to disturbances both of growth and health.

Vater and Minerals

Although from 60 to 70 per cent of the human body is water, this is not sually considered food because it is obtained at a negligible cost. The me may be said of oxygen. The importance of water and oxygen, how- ver, becomes apparent when there is a deficiency or a total lack of either, r then life ceases.

The animal body is a balanced system of aqueous solutions or dispersions, ept at a constant temperature (37° C., or 98.6° F.) which is usually much gher than the surrounding environment. Consequently, a part of the ater is continuously evaporating and must be replenished. This con- nuous evaporation utilizes about 25 per cent of the heat produced by the man body. The water evaporates continuously from the skin, and hen the rate is rapid and the surrounding air is near the moisture satura- on point (high humidity), perspiration occurs. Water is also lost through ie excretion of waste products in the urine and feces. A total of two to ree liters of water (three quarts) is lost per day by an average-sized man oing moderate work in a temperate climate. Part of the loss is replaced om the water in foods and beverages and the rest by drinking.

Physiologists and biochemists have shown that a certain number of organic ions, such as magnesium, Mg^{++}, and calcium, Ca^{++}, must be pplied to plants for growth and normal functions. Likewise, inorganic ns are necessary to animal life. Some of the inorganic ions that must be pplied for normal human nutrition are calcium, Ca^{++}, phosphate, O_4,$^{\equiv}$ chloride, Cl^{-}, sodium, Na^{+}, potassium, K^{+}, magnesium, Mg^{++},

iodide, I^-, ferric, Fe^{+++}, cupric, Cu^{++}, and manganous, Mn^{++}. They ar often called minerals. The first two are the prime builders of bones, th chassis of the animal engine. The chloride ion is involved in the secretion o hydrochloric acid in the stomach; iodine is essential to the function of thyroi glands, and iron is necessary for hemoglobin formation; copper and manga nese, together with iron, are involved in the oxidative processes of the body

Most of the inorganic ions are present in the plant and animal tissues o foods; there are some, however, particularly Ca^{++}, $PO_4^{\equiv}$, and Fe^{+++} which are not in great abundance, so that certain diets may lead to defi ciencies in these elements and give rise to grave disorders, such as stunte growth, rickets, anemia, and goiter. Protection against such deficiencie is of greater importance during the period of growth, when the diet shoul include foods rich in these elements.

Vitamins

The term vitamin is used to designate certain nutritive organic com pounds which must be present in small amounts in the diet of animals fo normal development and functioning. Deficiency or absence of a vitami from the diet leads to disturbances in some specific function and ultimatel leads to bodily derangement or disease. For example, deficiency of vita min A causes night blindness; deficiency of vitamin D causes rickets; an deficiency of nicotinic acid — a constituent of the complex vitamin B — causes pellagra.

The knowledge of vitamins was elicited almost entirely through con trolled nutritional experiments, mostly through the use of the lowly an despised rat. In 1913 American investigators noticed that rats could no grow normally if fed with diets which contained purified fats, but tha their condition was improved when butter fat and cod liver oil were added The conclusion was reached that certain fats carry a small amount of required nutrient; this factor was named fat-soluble A, and is now know as vitamin A. The entire vitamin research has been guided by experi ments of this type: first, to find a food rich in the particular vitamin; next to control the concentration of a food extract that is rich in the vitamin and finally, to standardize the vitamin concentrate. Because the chemica nature of a vitamin in the beginning is unknown, the vitamins are desig nated by letters (A, B, C, D, and so on). In many cases, what was origi nally thought to be one vitamin (for example, vitamin B), was progres sively found by continued research to contain several factors or differen substances, B_1, B_2, B_3, and so forth. Vitamin B_1 is also known as thiamin and B_2 was renamed vitamin G or riboflavin. In fact, from vitamin I complex six distinct vitamins have been isolated whose structures ar known, and undoubtedly a few more essential food factors remain to b discovered. Deficiency in any of these factors causes certain symptoms o diseases in experimental animals. When a sufficient amount of a vitamin ha been prepared in the pure state, the problem of its chemical structure is take

TABLE 60. LIST OF VITAMINS

Vitamin	Chemical Name	Functions[1]
Vitamin A Group		
Vitamin A_1	Axerophthol	Promotes growth; helps maintain normal resistance to infection; maintains visual adaptability to dim light. Deficiency leads to serious eye disease.
*Vitamin A_2		
*Vitamin A_3		
Vitamin B Group		
Vitamin B_1	Thiamin	Promotes growth; involved in oxidation changes; essential to normal functioning of nerves. Deficiency of B vitamins causes serious disturbances, among them neuritis, beriberi, pellagra.
Vitamin B_2	Riboflavin	
*Vitamin B_3	Pantothenic acid	
*Vitamin B_4	Biotin, Arginine	
*Vitamin B_5	Nicotinic acid	
Vitamin B_6	Pyridoxin	
*Vitamin B_7		
*Vitamin B_8	Adenylic acid	
Inositol		
p-Aminobenzoic acid		
Vitamin C	Ascorbic acid	Essential to formation and maintenance of teeth, bones, and blood vessels; increases resistance to infection and hemorrhage; important in oxidation and reduction reactions in the body. Deficiency causes scurvy.
Vitamin D Group[2]		
D_2, D_3, D_4, D_5, D_6	Viosterol (calciferol)	Important in the utilization of calcium and phosphorus, and hence in the building and maintenance of bones and teeth; prevents rickets.
Vitamin E Group	Tocopherols (α, β, γ)	Involved in cell maturation and differentiation and in reproductive processes.
Vitamin H	Biotin	Involved in fat metabolism.
Vitamin K_1 and K_2		Necessary for normal blood coagulation.
Vitamin P	Citrin	Involved in maintaining normal function of small blood vessels.
Vitamin L_1 and L_2		Necessary for normal lactation.
Folic Acid		Stimulates growth in rats and some bacteria.
Factor T		Involved in regulation of blood vessels.

[1] Described only in general terms for each vitamin group.
[2] Individual members of this group have not been named yet.
* Vitamins not definitely identified.

up, so that in a comparatively short time the nature of the vitamin is determined. In this manner the synthesis of vitamins has been accomplished.

Table 60 lists both the vitamins which have been identified and also those which have not been definitely identified; by identification is meant proof that the vitamin is identical with an organic compound whose properties are known. Those which have not been definitely identified are marked by an asterisk. The functions or physiological actions of the vitamins are described in a very general and condensed manner in the last column of the table. The sources of vitamins are common foods, so that by a selection it is possible to obtain the amounts needed for normal functioning. There is evidence that a number of vitamins (including thiamin and ascorbic acid) can be used in therapeutic and preventative medicine. This, however, is not a license for the indiscriminate addition of an excess of vitamins to the diet. There is a tendency in the advertising of foods to use the alleged vitamin content as a sure protection against one or more diseases. Needless to state, such advertisements should be scrutinized and viewed with suspicion.

Metabolism

Before a discussion of the daily requirements of nutrients is given, it is advisable to consider briefly what happens to foods in the animal body. Through the process of digestion, the complex molecules of carbohydrates, fats, and proteins are reduced to the simple sugars, amino acids, and simple organic acids. These, together with water and inorganic ions, finally pass through the intestinal wall to the blood and lymph; and, together with the oxygen taken through the lungs, are carried to all the tissues and are therefore the nutrients of the cells. Through complex chemical reactions the protoplasm of the cells utilizes these simpler substances to build the characteristic tissues of the animal body, and produces the energy by which life is sustained. These complex chemical reactions are included under the term *metabolism.*

In the metabolism of carbohydrates, the simple sugars which enter the blood stream are synthesized to glycogen in the liver and muscles, leaving a constant amount of 0.1 per cent of glucose in the blood. The glycogen in the muscles is directly related to the performance of work. As the muscle contracts, the blood sugar undergoes oxidation to furnish energy; then the sugar supply in the blood is replenished by the glycogen. The processes by which the sugar is oxidized are very complex and need not concern us here. As shown in Chapter 33, all the different changes may be summarized by the equation:

$$C_6H_{12}O_6 + 6\,O_2 \longrightarrow 6\,CO_2 + 6\,H_2O + \text{Heat}$$

In the metabolism of fats, a small part is left in the circulatory tissues, while the major part is deposited as a reserve fuel to be drawn upon in time of scarcity. Energy is derived from the enzymatic oxidation of fats. The

ong-chain fatty acids are oxidized in steps, two carbon atoms being involved n each step. The final products are carbon dioxide, water, and energy.

In the metabolism of proteins, the body is able to synthesize its particular nd specific proteins from the amino acids supplied through the digestion f foods. In the chemical reactions which enable the body to carry on its ital activities, the proteins undergo oxidation and decomposition. The nd products are carbon dioxide, water, and ammonia. While the carbon lioxide is carried through the blood stream and exhaled through the lungs, he ammonia is eliminated by a process involving the conversion of mmonia and carbon dioxide into a compound called *urea*:

$$CO_2 + 2\,NH_3 = \underset{\text{Urea}}{CO(NH_2)_2} + H_2O$$

he urea passes into the blood stream, and is eliminated through the xcretory system as a dilute water solution (urine).

luman "Miles per Gallon"

The animal body has been compared with the steam engine and the utomobile engine as a converter of chemical energy to heat and mechanical nergy. Although the two types of converters differ in construction, one eing a strong metallic engine, the other an arrangement of fragile tissues, ssentially the same type of reaction occurs in both. Compounds of car- on (coal, gasoline, foods) are oxidized to produce carbon dioxide, water, nd heat. Therefore it is reasonable to inquire about the relative effi- iency of the two types of engines in converting fuel to work. It is a com- non experience to inquire how many miles per gallon an automobile ravels; the same question may be asked about the human engine.

In comparing the animal to the gasoline engine, two distinctions should e made. One concerns the temperature at which the engine operates. n man, the temperature seldom rises above 37° C., while the temperature n the chamber of a gasoline engine rises far above 1000°. The other and nore important distinction is that the metallic engine consumes no fuel hile "resting in the garage," whereas the animal utilizes fuel even during

For the life activities even while resting, the adult uses for every 100 pounds of body weight —

1060 Calories in every 24 hours or 1 Calorie an hour for every 2.2 pounds (1 kilogram) body weight.

Sitting quietly 1.4 Cal. per hr. for every kg.

Walking 3 Cal. per hr. for every kg.

Going upstairs 15.7 Cal. per hr. for every kg.

Typing 2 Cal. per hr. for every kg.

Running 8 Cal. per hr. for every kg.

Different amounts of energy (Calories) are needed for different kinds of activities.

FIGURE 316

sleep. The internal processes of digestion and circulation are uninterrupted from birth to death. The heat utilized for these internal processes in order to sustain life is called *basal metabolism.*

How many Calories (large) per hour are required by a human adult at rest and comfortable? This would be the energy required for basal metabolism. If one wishes to find the "miles per gallon" for an automobile, he goes to the service station. The mechanic disconnects the carburetor and puts in its stead a graduated bottle which contains gasoline. The reading of gasoline in the bottle and the mileage in the speedometer are taken, the car being driven at a speed of forty to forty-five miles per hour and after a certain number of miles have been traveled the readings are taken again. To determine the "miles per gallon" in man is quite difficult; nevertheless, it can be done. The first thing is to measure the energy required for basal metabolism. This is done by using a calorimeter. A large number of studies show that an average adult uses one Calorie of heat per hour for every kilogram (2.2 pounds) of body weight. Thus a person weighing 150 pounds (68 kilos) and completely at rest requires 68 Calories per hour, or about 1600 every twenty-four hours, to keep life going. It should be noted that the term Calorie here is the *large* calorie which is 1000 small calories; in other words, the large Calorie is the amount of heat required to raise the temperature of 1000 grams (1 kg) of water 1° C. This then would be equivalent to 41,800,000,000 ergs of work.

It is clear that for any activity of the body additional calories are required over and above the basal requirements. For every kilo (2.2 pounds) of body weight the additional Calories required per hour for various activities are: walking, 2 Calories; dishwashing, 1 Calorie; sweeping, 1.4 Calories; typing, 1 Calorie; sawing wood, 5.7 Calories; swimming, 7.9 Calories; walking upstairs, 14.7 Calories. It may be surprising that walking upstairs requires twice as much energy as the hardest work. But walking upstairs is very hard work — it is lifting one's body against gravity. It is therefore possible to estimate the total calorie requirements, provided the type of work in which a person is engaged is known. The figures in Table 61 will serve as examples:

Table 61. Calorie Requirement of Various Persons

Description of Person	Weight in Pounds	Total Calories Required per day
Men, 20–59 years	154	
Very active work		4500
Moderately active work		3000
Light work		2700
Sedentary work		2400
Women, 20–59 years	132	
Very active work		3000
Moderately active work		2500
Light work		2300
Sedentary work		2100

Children need more calories per pound than middle-aged adults to meet the demands of growth and greater physical activity, while old people need less. For example, the activity of a boy eleven to fifteen years old requires as many calories as heavy work.

The heat requirements of a hard-working man do not appear very large compared with the heat derived from fuels. One gram of coal liberates about six Calories and one gram of gasoline about ten Calories; thus the heat from one pound of gasoline is more than sufficient for the daily requirements of a hard-working man. It has been shown (Chapter 21) that only a fraction of the heat produced by the combustion of fuel is converted to useful work. Steam engines have an efficiency (at best) of about 10 per cent; and a gasoline engine, of 20 to 25 per cent. The efficiency of the animal body compares very favorably with that of the gasoline engine. When a new automobile and a young man or a young cow are compared, the results are in favor of the animal converter. The animal converts 35 per cent of the energy of the fuel into work as compared with the 25 per cent converted by the gasoline engine.

From the above discussion it is evident that the diet should contain: (*a*) a sufficient amount of carbohydrates and fats to furnish the calorie requirements; for an adult doing light work 400 g (14 oz.) of carbohydrates and 50 g (1.8 oz.) of fats supply the calorific requirement; (*b*) a sufficient amount of mixed proteins (minimum 60–70 g or 2 oz.) per day; (*c*) the required amount of inorganic ions (1 g of Ca, 0.9 g of P, and 0.2 g of Fe); the required amount of vitamins, water, and fibrous material for normal functioning. It is possible by application of the knowledge obtained from nutritional studies to obtain all the requirements and at the same time satisfy all psychological factors such as likes, dislikes, and whims. Health depends on the proper balance of the nutritive requirements, and the information has been simplified so that everyone can understand it.

SUMMARY

1. Fuels and foods are mixtures of compounds of carbon and hydrogen. The chemical changes which occur during their combustion in heat engines or animal bodies are oxidation reactions. The ultimate products are carbon dioxide and water — and liberation of heat.
2. The chief fuels used as sources of energy in the United States are coal and petroleum; together they make up 91 per cent of the total annual energy utilized.
3. Coal is altered plant débris from previous geological ages. The transformation of wood to coal takes place in stages: *peat*, *lignite*, *bituminous*, and *anthracite*. In the transformation the percentage of volatile matter decreases and fixed carbon increases.
4. Petroleum is a complex mixture of hydrocarbons derived from sedimentary strata; it is separated or refined by fractional distillation into light fractions

of gasoline and kerosene and heavy fractions of fuel oil and lubricating oils. The higher fractions when heated under pressure are "cracked," or partially converted into lighter fractions. In such processes, hydrocarbons of high molecular weight are converted to smaller molecular fragments.

5. The consumer aspect of fuels is important. The scientific method of buying fuels is in terms of B.T.U. contents.
6. The essential nutrients present in foods are water, salts or minerals, carbohydrates, fats, proteins, and vitamins.
7. Carbohydrates include starches and sugars and compose about one-half of the average diet. Most carbohydrates used in diets are built up of glucose units. Glucose is a complex hydroxy-aldehyde; cane sugar and starch yield mainly glucose on digestive hydrolysis.
8. Fats are esters of glycerol and long-chain acids. Unsaturated fats like cottonseed oil can be converted to solid or hardened fats by addition of hydrogen to the unsaturated compounds.
9. Proteins are complex compounds of high molecular weight formed by union of many amino acid molecules. In the body, proteins are converted by digestive hydrolysis to amino acids.
10. Water makes up the largest part of tissues. It provides a medium for the complex reactions of the living cells.
11. The inorganic ions necessary to animal life are sulfate, phosphate, chloride, iodide, sodium, potassium, magnesium, calcium, ferric, cupric, and manganous.
12. Vitamins are complex organic compounds required in very small amounts in the diet of animals for normal development and functioning.
13. Metabolism designates the complex chemical reactions through which the living cells utilize the simple nutrients supplied in foods to obtain the energy by which life is sustained. The amount of energy (measured in Calories) required for body functions (aside from work and normal activity) is the *basal* metabolism.

STUDY EXERCISES

1. Find the amount of the gas bill in your home for the past month. From the number of therms given in the bill calculate: (*a*) the number of B.T.U.'s; (*b*) the number of calories; (*c*) the amount of coal necessary to produce the same quantity of heat; (*d*) the cost if the same quantity of heat were obtained from coal, natural gas, fuel oil, and electricity.
2. Prior to 1930, not much attention was given by the public to hydroelectric power development. What factors brought about a change? What factors must be taken into consideration in hydroelectric power development?
3. Draw a diagram to show the progressive change of wood into anthracite. Indicate (*a*) the type of geologic processes which brought about each change; (*b*) the nature of chemical changes in each stage — that is, which elements were diminished or increased. (Refer to Table 56.)

4. A certain amount of Pennsylvania coal is anthracite, but all that of Illinois is bituminous. What information can be deduced as to the past geologic history of the two respective coal regions?

5. In what type of strata is petroleum sought? Make drawings of two types of geologic structures which show conditions for oil-well drilling operations. Draw a rough diagram showing the operations of petroleum refining. Give the various fractions and their uses.

6. In the following are listed a series of foods. Place before each item the letter *C* if it contains a considerable amount of carbohydrates, *F*, of fat, *P*, of protein, *V*, of vitamins — followed by letters designating the particular vitamins in each case: if the food is a rich source of these vitamins, VAB_1 would designate that the food is rich in vitamins A and B_1. Place also the letters *Cel* if the food contains a large amount of cellulose fibers, and *M* if it is a rich source of minerals, *EW* if the water content of the food exceeds eighty per cent.

.... Carrots and yellow vegetables	.... Cane sugar	.... Peas
	.... Honey	.... Cabbage
.... Eggs	.... Milk	.... Oranges
.... Lean meats	.... Corn oil	.... Rice
.... Fish	.... Bread	.... Bacon
.... Tomatoes	.... Butter	.... Cream
.... Potatoes	.... Apples	.... Spinach
.... Green, leafy vegetables	.... Peanuts	.... Gelatin

7. The following materials are heated under pressure with water for twenty-four hours. The water may contain small amounts of H^+ or OH^- to accelerate hydrolysis. Place after each substance the names of the chief hydrolytic products which will result:

Egg albumen.....	Butter.....	Linseed oil.....
Wood.....	Milk sugar.....	Gelatin.....
Cane Sugar.....	Ordinary paper.....	Lean meat.....
Straw.....	Starch.....	Cheese.....
Olive oil.....	Bread.....	Lettuce.....
Lard.....		

8. Assume that you are doing hard work for four hours per day and light work for the remainder of your waking time. Calculate your weekly calorie requirements. Base the calculations on your body weight.

9. On the basis of the figure obtained in Exercise 8, calculate the amount of (*a*) carbohydrates, (*b*) fats, (*c*) proteins that you need. Give the amounts in grams of dry weight and also in ounces.

10. Why is it possible to use hay and straw as foodstuffs for livestock and not for human beings? Can powdered straw be treated in some manner so that it may be used as food? Explain.

11. An animal which receives only gelatin for its protein requirements does not show normal growth. To what may this be ascribed?

12. Discuss the contribution of the science of chemistry to the health and welfare of the community.

FOR FURTHER READING

1. United States Department of Agriculture, *Yearbook of 1939 — Food and Life.*
   One of the most extensive reference books on foods. The first 94 pages consist of a summary of the book and is written for the layman. An excellent reference book.
2. Hatcher, W. H., *An Introduction to Chemical Science*
   Chapters 31–34 give a good discussion of foods and diet.
3. Strong, Ralph K., *Chemistry for the Executive*
   Chapter 14 gives a discussion on fuels and Chapter 13 on foods.
4. Babor, J. A., *Basic College Chemistry*
   Petroleum and its products are discussed on page 625, foods on page 649.
5. Briscoe, H. T., *College Chemistry.*
   Chapter 24 gives a discussion of coal; Chapter 33, gasoline and refining of petroleum; the chemical nature of foods is discussed on pages 452–453.
6. Arber, Edward Alexander N., *The Natural History of Coal.* London: Cambridge University Press, 1912.
   This little book is written by a geologist primarily for the layman. It gives the probable origin and accumulation of coal.
7. Consumers' Counsel of the National Coal Commission, *Know Your Coal.* Washington: Government Printing Office, 1938.
   An excellent pamphlet of 11 pages which every buyer of coal should read. It may be obtained from the Superintendent of Documents, Washington, D.C. at the price of ten cents. It is written in non-technical language and presents the facts about coal that every consumer should know.
8. Leighou, R. G., *Chemistry of Engineering Materials.*
   This technical book deals with the properties of the materials employed in the construction and operation of buildings and equipment. Chapter 2 discusses fuels of all types.
9. Carr, Arthur R., and C. W. Selheimer, *Fuels and Heat Utilization.* New York: Pitman Publishing Corporation, 1940.
   This is a short text and laboratory manual for the student who wishes detailed information on fuels and their applications.
10. Riegel, E. R., *Industrial Chemistry.*
    Chapters 12 and 14 give a discussion of the practical applications of fuels for generation of steam and other industrial purposes.
11. McCollum, Elmer V., and Nina Simmonds, *The Newer Knowledge of Nutrition.* New York: The Macmillan Company, 1939.
    An excellent book on nutrition. Chapters 1 and 2 deal with the beginning of a new era in nutrition and the biological methods used in the analysis of foods. These two chapters are recommended for the general student. The chapters on vitamins are thorough though somewhat technical.
12. Prescott, Samuel C., and Bernard E. Proctor, *Food Technology.* New York: McGraw-Hill Book Company, 1937.
    A non-technical book on the production, preservation and processing of foods. Information is given on all types of foodstuffs.

35

Electrons in Motion

N PRECEDING CHAPTERS we have seen that a study of the electric charge as pointed the way to an understanding of the nature of matter and of nemical change. Atoms which until recently were thought to be the ltimate particles of matter are now regarded as complex aggregates of ore fundamental electrical particles — electrons, protons, and neutral rticles called neutrons. The massive and stable but very compact ortion of the atom, the nucleus, is thought to consist of protons and eutrons. Around this nucleus move the electrons in different orbits or nergy levels. It is the outermost group of electrons which we have seen etermine, to a large extent, the chemical character of the element. In is electrical theory of matter we have found the long-sought answer to e riddle of the chemical union of atoms and the forces which bind them gether in stable molecules.

It has been shown that our foods and many other organic compounds iginate in plant life. They are the products of an extraordinary series chemical reactions which begin with photosynthesis and in which rbon dioxide undergoes a partial reduction. The food, in turn, is uti-ed in the body where much of it is oxidized to yield energy. In the mplex compounds involved in these processes and in many other com-unds the atoms are held together by the sharing of electron pairs. neir formation or breakdown involves the partial transfer of electrons. other chemical changes electrons move completely from one atom another. An active metal, for example, gives electrons to a non-etal and the resulting ions which comprise the compound so formed are ld together by the powerful forces of electrostatic attraction. If we sh to reverse the chemical change between the metal and non-metal, e must find a way to transfer the electrons from the negative to the sitive ion. This change requires energy, and the *electric current* has en most successfully applied to the difficult cases. Aluminum, mag-sium, chlorine, and many other elements are prepared by the process of ectrolysis.

But we must now leave the subject of matter to consider in more detail

the subject so intimately allied to it — electricity. We shall first inves gate the electric current, its production, its effects and uses, and its natu We should bear in mind as we continue this study that the *electric curre which so readily brings about chemical change was first produced by chemic reaction.*

The Electric Current

That the electric current which flows ordinarily on copper or aluminu wires is a form of energy is indicated by two facts. First, it is readi converted into other forms of energy, heat by the incandescent lam mechanical energy by the motor, and chemical energy by the electrolyt cell. Second, the electric current is always generated by the expenditure one of these forms of energy and a "static" charge is also developed by t use of mechanical energy.

But the "static" electricity which for a long time was assumed to stationary and to reside firmly attached to the object on which it w generated, will move about on a conductor. This significant fact was fi observed by Otto von Guericke (1602–1686), who found that a piece thread, no doubt damp, carried off some of the charge from an electrosta machine.

Having established that electricity "flows" we must now determine i nature. The evidence that electricity is atomic, namely, Faraday's laws electrolysis (Chapter 37) and the measurement of the value of the fund mental charge have already been cited. The kind of charge (positive negative) on the mobile particles is indicated by a number of experiment phenomena. In chemical reactions of oxidation-reduction, electrons, eas detached from the outer part of atoms, are transferred from one substan to another. In the cathode ray tube and the X-ray tube streams of el trons flow across the space from cathode to anode as a part of the elect circuit. In the photoelectric cell and the electron (hot filament) tube, bo of which are treated in this chapter, a flow of electrons in one directi across a gap completes the electric circuit. These facts suggest that *el trons in motion on a conductor or across an empty space constitute the elect current.*

Electricity from Chemical Energy

A Chemical Source of Current is Discovered. Investigations in stat electricity stimulated much interest in this subject during the latter pa of the eighteenth century. Many demonstrations were made at publ gatherings with the Leyden jar and the queer sensations or shock it pr duced if allowed to discharge through the body. At about that time a electric eel or torpedo ray, a fish, was brought to Europe from Afric This animal, known to the early Greeks, is able to inflict a shock whi

as observed to be similar in sensation to that received from a charged eyden jar. So-called animal electricity was the subject of much discus- on and some investigation. The Italian physiologist, Ludigi Galvani, bserved, so the story goes, muscular movements in a frog's leg when one its nerves was touched by a metal instrument exposed to the spark fects of a static generator or even an electric storm. Further experi- ent showed that the same effect could be produced without the electric scharge if two unlike metal wires were joined and their free ends were in ntact with the animal tissues. He concluded that "animal electricity" as discharged through the wire and produced the muscular effect, and in 91 he published his work on this subject.

Galvani was wrong. The electricity came from the metals, for they, gether with the fluids in the animal tissues, constituted the first cell for e conversion of chemical energy to electricity. That Galvani was in- rrect in his conclusions was demonstrated by his friend Alessandro Volta, ofessor of Physics at Pavia, Italy. After careful study and experiment, lta became convinced that the effect obtained by Galvani was due to ctricity which could be produced quite independently of the animal sues. He constructed what is known as a *voltaic pile*, each cell of which nsisted of cloth or leather soaked in salt solution and placed between late of copper and one of zinc. The electric effect or potential was atly multiplied by placing a series of such plates in a pile (Figure 317), h pair of plates separated from the next pair by a wet pad. Volta found t a battery constructed of from seventy-five to a hundred pairs of plates, cells, gave a surprising shock when he placed a hand on each of the reme terminals. The more amazing thing, however, was that, unlike Leyden jar, the shocks could be obtained repeatedly without recharg- each time.

Volta constructed many batteries by using different combinations of tals and finally used glass vessels in which the salt or alkali solutions l the metals were placed. He was not able to measure the voltage of batteries, for the magnetic effect produced by the current — the prin- le upon which our measuring instruments are based — was yet to be covered. Since he had no electric meters he was forced to judge the ctiveness of the pile or battery by the extent of shock inflicted. He ced one hand on an extreme terminal and ran the other one over the cessive cells of the pile, observing the increasingly intense shocks. ta published, by letter in the year 1800, the result of his researches — phetic of the great advances which were to be made in the new century.

Simple Cells. We may now extend our inquiry. How does a chemical ction produce and propel a stream of electrons? Volta's use of his teries was for short intervals, and he thus believed that in them he had unlimited source of current. Had he used any of his batteries steadily any length of time, he would have found that they would run down or

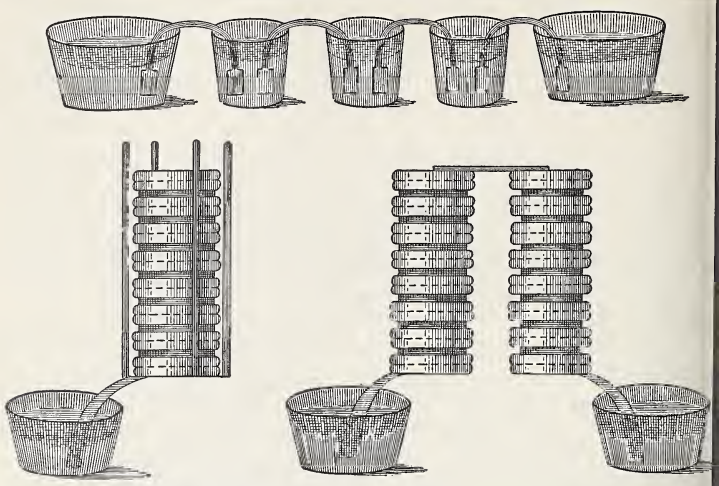


FIGURE 317. VOLTAIC PILE AND BATTERIES — FIRST CHEMICAL SOURCE OF THE ELECTRIC CURRENT
(*Philosophical Transactions of the Royal Society, 90, 430 [1800]*)

discharge. Something must therefore be replenished just as for any other source of energy. (First Law of Thermodynamics.)

It may be recalled (Chapter 30) that chemical reactions of oxidation-reduction are those in which electrons go from one substance to another. The substance which loses the electrons is known as the *reducing agent*, and the one which receives the electrons as the *oxidizing agent*. These substances may be elements in the free state or compounds or ions. In ordinary chemical processes these substances are brought together into intimate contact for the transfer of electrons. Zinc metal, for example, is a reducing agent, while copper (cupric) ion, a constituent of cupric salts, is an oxidizing agent. When they are placed together in a beaker (Figure 318), the zinc gradually is consumed, the blue color of the copper ion fades, and particles of metallic copper appear. Zinc displaces the copper of the compound, or, more precisely, zinc reduces cupric ion to copper and is itself oxidized to zinc ion, which passes into solution. A reacti

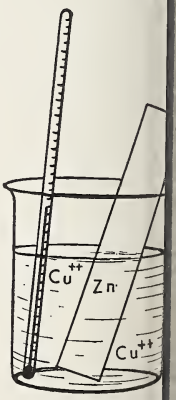


FIGURE 318
Heat from chemical re
tion of oxidation-red
tion when the oxidiz
and reducing agents
in contact with each ot

f oxidation-reduction has taken place and may be represented in the ymbolism of the chemist:

$$Zn + Cu^{++} \longrightarrow Zn^{++} + Cu + \text{heat}$$

wo electrons go from each zinc atom to a copper ion, thus giving us a clue ı which to work. The energy of this reaction produces heat, as shown by thermometer placed in the solution.

Now we place the zinc in one beaker and copper-sulfate solution in ıother. The zinc is immersed in water in which some zinc sulfate is dis-lved. In the copper-sulfate solution is placed a strip of copper (Figure .9). Both metals tend to lose electrons, but both metal ions more or less nd also to gain electrons. The zinc is the better loser (reducing agent), ıd the cupric ion is the better gainer (oxidizing agent); so the reactions oceed:

$$Zn \longrightarrow Zn^{++} + 2e \quad (1)$$

$$Cu^{++} + 2e \longrightarrow Cu \quad (2)$$

ıe electrons lost by the zinc accumulate on the zinc plate, giving it a gative charge, and the Cu^{++} ion removes electrons from the copper plate, ıving it with a positive charge. Thus a potential difference is built up tween the two plates. The potential difference does not become very eat, for an accumulation of electrons on the zinc tends to retard action), and the deficit of electrons on the copper prevents more cupric ions)m receiving them, and thus action (2) is retarded. When the two plates e connected by a metal conductor, *electrons flow* from zinc to copper and th reactions continue, thereby producing an *electric current*, which is dicated by the galvanometer *G* placed in the circuit. *Thus, two chemical bstances may react with each other at a distance, provided the reaction is one*

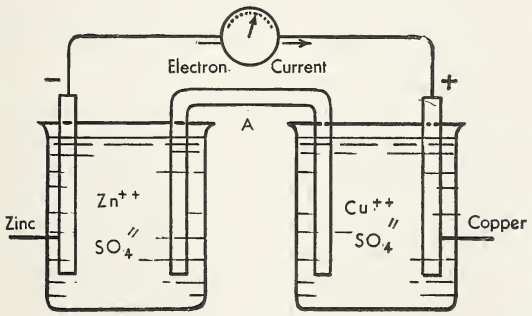


FIGURE 319

Electric current from the chemical reaction of oxidation-reduction. Electrons flow ough a conductor from the reducing agent (Zn) to the oxidizing agent (Cu^{++}).

of oxidation-reduction; and such reactions may be utilized to produce an elec tric current. The total reaction involves equations (1) and (2), and thi time there is no rise in the temperature of the solution.

$$Zn + Cu^{++} \longrightarrow Zn^{++} + Cu + \text{electric energy}$$

The salt bridge *A* is also essential for the operation of the cell. It i filled with a solution of an ionic compound like sodium chloride whic will not react with either the plates or the solutions and which serves t keep the solutions around the electrodes neutral. The formation of zin ions would give the solution surrounding the zinc plate an excess of positiv ions, and the reduction of the cupric ions at the copper plate would giv that solution an excess of negative ions. The flow of ions to or from th solution in the salt bridge prevents such trends and maintains electrica neutrality in both solutions.

In actual practice the plates and solutions may be placed in one containe and the metal ions kept more or less separate by a porous container aroun the zinc or by gravity, the heavier copper ions sinking to the bottom. This is exactly the type of cell developed by Daniell in England and widely used soon after Volta announced his discoveries. If we apply the principle of equilibrium to reactions (1) and (2), it is apparent that in order to maintain the highest potential the zinc ions should be kept at a minimum concentration and the cupric ions at a maximum concentration. For practical purposes the concentrations are such that the potential difference between the plates is 1.1 volts.

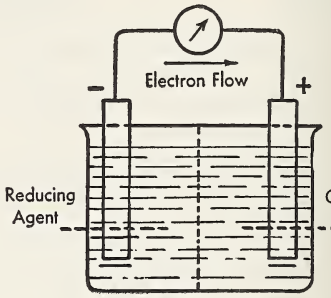


FIGURE 320
GENERALIZED CELL FOR PRODUCTION O CURRENT BY CHEMICAL REACTION

A Generalized Cell. The rather full description of the Daniell cell ma serve as a pattern for all other cells used for the conversion of chemica energy into electric energy and thus permit us to generalize. Such a ce must have a reducing agent which may serve as the minus electrode c plate, as does the zinc in the Daniell cell, or which may be a part of th solution around this plate or even a gas absorbed on the surface of th plate. It must also have an oxidizing agent (Figure 320) which ma serve as the positive electrode or plate or which may be in contact wit the positive plate. When the reacting chemicals are in solution aroun the plates, inactive electrodes like platinum or carbon are used. In a cases the electrons flow from the reducing agent to the oxidizing ager

hrough the external wire until the connection is broken or one of the hemicals is consumed.

If one wishes to invent a new cell or battery, he cannot do so by a simple election of any reducing agent as the electron source and any oxidizing gent as the electron receiver. Copper, for example, may act as a reducing gent under some circumstances and zinc ion is an oxidizing agent, but the wo do not react with each other. In order to aid in the selection of suitble chemicals, a brief table, commonly called the activity or electromotive eries, may be referred to (page 550). The substances are arranged in two olumns, one for the element in the reduced state, the other for the same lement in the oxidized state. Sodium, for example, in the reduced state s the metal or free element and is a very strong reducing agent. It is herefore placed near the top of the list of reducing agents. Its ion repreents the element in the oxidized state but is not a good oxidizing agent; or it can take electrons only from better reducing agents than sodium. odium ion is, therefore, placed among the poorest of the oxidizing agents. n the other hand, silver is a very poor reducing agent, while the silver n is a good oxidizing agent; both are appropriately placed in the lower art of the table.

In general, any substance in the reduced state will give electrons to any those in the oxidized state below it in the table. Conversely an ion or element in the oxidized state will take electrons from (oxidize) any one in the reduced state above it. Nickel will reduce silver ion to silver, or, conversely, silver ion oxidizes nickel to nickel ion. Aluminum ion will not oxidize copper, nor will copper reduce aluminum ion. Such a table, which is the product of experiment with cells, tells us much about the relative activity of the various elements and compounds.

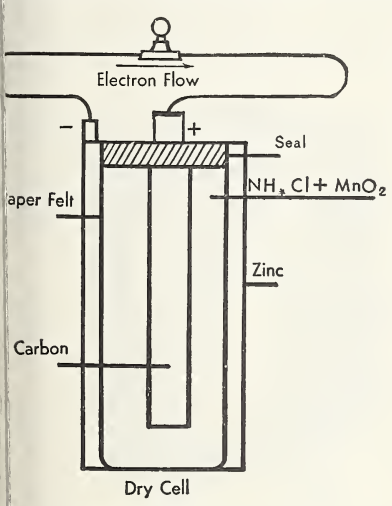


FIGURE 321. DRY CELL

Much of our output of zinc is used in dry cells as a source of electrons.

Cells and batteries are useful tools for the experimenter, and two types are of considerable everyday use — dry cells and storage batteries.

Dry Cells. Dry cells are extensively used in flashlights and other portable devices where current is needed only for brief intervals. A zinc container serves as the

negative electrode, or electron source, and a carbon rod as the positiv electrode. Packed between the electrodes is a moist mixture of chem cals, among which are manganese dioxide, zinc chloride, and ammoniu chloride. A moist blotter-like cardboard separates the mixtures fro the zinc electrode (Figure 321). In reality, therefore, the cell is we Upon discharge zinc loses electrons, which move through the wire an light a lamp or do some other work and are received by the chemica around the carbon electrode. It is not feasible to reverse the curre through these cells, or the Daniell cell, or other voltaic cells, in order t restore the chemicals consumed by discharge. In that case, they would b storage cells.

The Lead Storage Battery. Unlike the primary cells described so fa the lead storage cell may be recharged. Electricity is not really store by such a process, however. Chemicals which are consumed during di charge are merely produced again when a direct current from an outsid source is sent through it in a direction opposite to that of discharge. Th principle of the lead storage cell was discovered in 1860 by accident — on of those fortunate accidents which occur sometimes and are observed b alert scientists who quickly see their significance. Gaston Planté, Frenchman, experimenting with a Daniell type of cell in the hope eliminating certain defects, had connected the electrodes of the cell t two lead plates immersed in sulfuric acid. After the experiment he acc dentally connected the lead plates to a galvanometer and the needle move Here was a reversible type of cell which was destined to be of great pra tical use.

The construction and operation of the lead storage cell may be unde stood by the use of a simplified cell somewhat like the one used by Plant The charged cell consists of two electrodes of lead — one coated with lea dioxide immersed in a solution of sulfuric acid (Figure 322). The lead the negative electrode, or electron source, and the lead dioxide the positiv

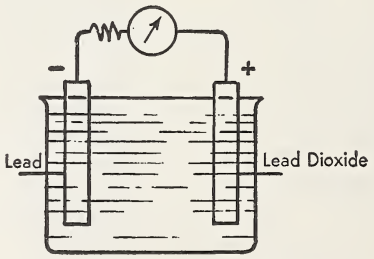


FIGURE 322. SIMPLIFIED LEAD STORAGE CELL

Electrons flow from the lead plate to the one coated with lead dioxide.

lectrode, or receiver of electrons. During discharge, chemical reactions ake place at the electrodes:

$$\text{At the } - \text{ electrode: } Pb \longrightarrow Pb^{++} + 2\,e$$
$$\text{At the } + \text{ electrode: } Pb^{++++} + 2\,e \longrightarrow Pb^{++}$$

he electrons move through the circuit to the Pb^{++++} in the lead dioxide. he lead ions react with the sulfate ions to form insoluble lead sulfate; and ne hydrogen ions of the sulfuric acid react with the oxide ions of the lead ioxide, forming water. The complete reaction is:

$$Pb + PbO_2 + 4\,H^+ + 2\,SO_4^{=} \underset{\text{charge}}{\overset{\text{discharge}}{\rightleftarrows}} 2\,PbSO_4 + 2\,H_2O$$

should be noted that during discharge sulfuric acid is consumed and the lates tend to become alike — coated with lead sulfate in which the Pb^{++} neither the oxidizing nor the reducing agent. When the battery is harged, the reverse reaction takes place: lead is restored to the one plate, ad dioxide to the other, and sulfuric acid is re-formed.

Actual commercial batteries, while reacting in precisely the same way, e more elaborate. More plates are used and are in the form of grids an antimony-lead alloy in which are packed the respective materials, ad and lead dioxide. These plates are placed alternately close together ith wood, glass-wool, or rubber separators between them. In each so-lled cell all the like plates are joined together in one unit, while in a ttery several cells are connected one after the other in series (Figure 323).

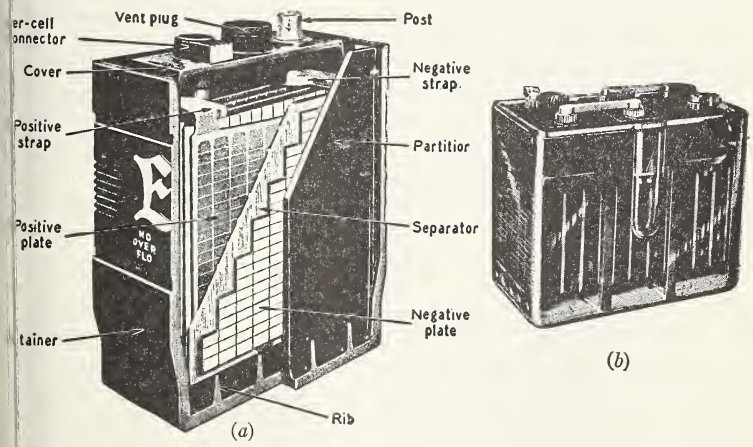


FIGURE 323. STORAGE BATTERY

(a) Complete cell cut away to show details of construction. (b) Complete battery of three s in glass container used in stationary services. (Courtesy of the Electric Storage Battery mpany)

The battery may be damaged unless certain precautions are observed in i care and operation:

(1) The battery should not be allowed to stand when uncharged or near discharged. The bulky lead sulfate which adheres to the plates ma cause them to buckle and to lose the active material from the grids.

(2) If the plates buckle to the extent that they touch, or, if for son other reason they are connected by a conducting substance inside of cell, the battery is internally *short-circuited*. Rapid discharge and re damage follow. The battery may be externally short-circuited by co necting the terminals by a good conductor such as a short wire or a pie of metal. If this is purposely done it should be for only a few seconds f the battery will, under the circumstances, deliver an enormous current as much as a thousand amperes.[1] Such a rapid discharge, if prolonged, wi overheat and permanently damage the battery.

(3) The level of the acid solution in each cell should be kept above th plates by the addition of distilled water.

(4) If charged too rapidly near the end of the charge, the battery ma be damaged by overheating. The extent of charge or of discharge is d termined by a measurement of the specific gravity of the sulfuric aci which reaches a value of 1.27 to 1.29 with full charge and drops to 1.15 t 1.17 at complete discharge. When fully charged, the cell voltage is 2. and when this value drops to 1.8 volts, the battery should be recharge

Against the disadvantages of such a battery's great weight and d terioration upon standing is its ability to supply quickly a very stro current. This decided advantage is due to the low internal resistance the cell, which is achieved by placing the plates very close to each oth (one-sixteenth inch) and by the use of an acid electrolyte. The hydroge ion moves through the solution quickly and is the best conductor of a the ions. It is for this reason that the lead battery is universally used i the automobile — it can quickly supply the energy required to operat the starter. For the airplane a more compact and lighter lead storag battery is used. It is equipped with a hood-like covering to receive th overflow of acid caused by tilting. When level, the acid returns to th cells.

The Edison Storage Battery. The plates in the Edison cell consist of iro which is the source of electrons, and nickelic oxide. The electrolyte potassium hydroxide. The Edison cell does not deteriorate upon standin is of rugged construction, and is not damaged by overcharging or di charging. It is lighter than a lead cell of equal power, but owing to th type of the electrolyte used and the fact that the plates are farther apar it has a higher internal resistance. Since it is more expensive and sinc it cannot supply quickly as large a current as the lead cell, it is not s widely used. The average discharge voltage is 1.2; hence a battery of fiv

[1] The ampere is the unit of electric current. See page 675.

ells is required to furnish the six volts supplied by the three-cell lead attery.

lectrons from Hot Metals

In the cells just studied, electrons leave the negative electrode, pass hrough a conductor, do work, and return to the positive electrode. The iving force is the inherent property of some substances, such as metals, lose electrons and of others to gain them. But in addition to chemical actions there are other methods by which matter may be forced to yield ectrons — the use of heat or light.

The Edison Effect. The emission of electrons from hot metals is known the *Edison*, or *thermionic effect.* The rapid loss of charge by hot metals as known for nearly two hundred years and was observed by Becquerel 1850 and later studied by Elster and Geitel, who used a hot wire in a cuum. While perfecting his incandescent lamp, which consisted of a rbon filament in a vacuum bulb, Thomas Edison was troubled by the posit of carbon on the inside of the bulb. In attempting to correct this fficulty he placed a metal plate P (Figure 324, *a*) in the lamp near the ament F and sealed its connecting wire into the glass. The tube was en evacuated to an extremely low pressure. When the plate was con-cted to the positive side of the battery B, which heated the filament, a all current passed through the plate and around to the filament. On e other hand, Edison found that when he connected the plate to the gative side of the lamp circuit (Figure 324, *b*), no current passed through e plate.

The Two-Electrode Tube. Edison, who developed so many practical vices, merely recorded his observations of this phenomenon, which was

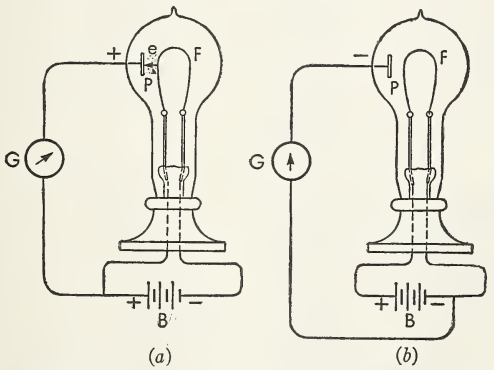


FIGURE 324. THE TYPE OF TUBE USED BY EDISON

Electrons move from a heated filament to a plate only if the plate is maintained at a positive potential.

destined to have such wide use and application in all types of radio tubes After the discovery of the electron, Thomson proved that electrons leav the hot filament of the tube and traverse the space to the positive plate. The one-directional flow of the electrons suggested its use to change alternating current (an electric current in which the direction of flow is reversed many times per second) to direct current. Alternating current is applied to the tube. Electrons cross the gap only from hot filament to cold plate and only during the half cycle when the filament is negative. The current, therefore, moves in only one direction through the tube.

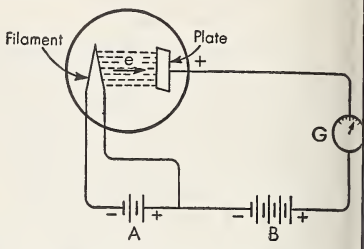


FIGURE 325. THE TWO-ELECTRODE VACUUM TUBE

Filament heated by current from battery emits electrons which flow to plate which connected to positive terminal of battery Galvanometer, G, indicates flow of curre through plate circuit.

Fleming, an associate of Marconi, saw in this tube rectifier possibilities for the detection of wireless waves. The Fleming valve, which was deve oped, is now used in the Tungar battery charger, the Kenetron rectifie the power supply tube in the radio, and the Diode detector (Figure 325 A filament coated with oxides of calcium or of barium or permeated wit thorium which, when heated, coats the surface, is commonly used. Suc a filament gives off electrons faster at dull red heat than tungsten does white heat.

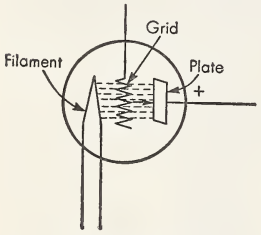


FIGURE 326
THREE-ELECTRODE TUBE

The introduction of a grid between the filament and the plate permits sensitive control of plate current.

The Coolidge X-ray tube (Chapter 44) is modified cathode ray tube in which a hot fil ment serves as a cathode. Electrons giv off are speeded on their way to the anode target by a very strong field. Their impa on the target causes the emission of the pow ful X-rays.

The Three-Electrode Tube. Another inve tion of very great importance was made De Forest, an American. The introducti by De Forest of a fine-wire mesh or *grid* tween the filament and plate gives a sensiti control to the flow of electrons (Figure 32 The grid, which is placed close to the filame is maintained at a small potential which m be varied and which may arrest or accelerate the flow of electrons from filament to the plate. A small positive potential increases this flow attracting the electrons which dart through the mesh to the plate.

egative potential may reduce or even stop the electron stream. Thus, small change in the grid potential produces a much greater change in the urrent through the tube, and a very weak current, such as may be in-uced by a radio signal, may be amplified. By the use of a number of ıbes the stages of amplifications are multiplied. Such tubes have made ɔssible the radio, public address systems, the long-distance telephone, ıe electric phonograph, sound motion pictures, and television, and they :e great aids in certain types of scientific research.

lectrons from Metals Exposed to Light

The Photoelectric Effect. Light shining upon a metal surface causes a ıenomenon known as the *photoelectric effect* which, in result, is similar thermionic emission. Electrons are given off from the metal and, like ose emitted from a hot wire, their motions may be controlled and used. ıat light exerted some electrical influence on metals was observed before e discovery of the electron. Hertz (1887), while experimenting with ctromagnetic waves (Chapter 44), found that sparks would jump a eater distance in air between zinc terminals if they were brightly il-minated. Soon thereafter Hallwachs performed experiments with a arged zinc plate which was connected to an electroscope and found that ra-violet light caused discharge when the plate bore a negative charge, t had no effect when the charge was positive (Figure 327). A neutral ıte acquires a small positive charge with a potential of approximately e volt; but when it is grounded, a greater charge is built up as the light shines on the plate.

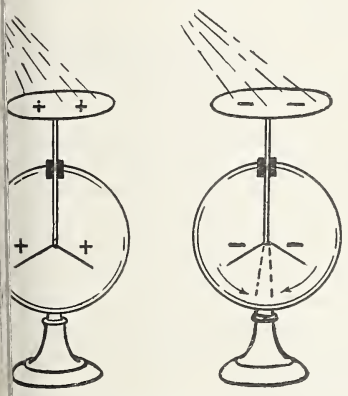


FIGURE 327

ltra-violet light brings about the dis-ge of an electroscope only if the charge t is negative.

One might explain the discharge of the electroscope by the presence of ions in the air; but identical results are obtained in a vacuum. This fact, together with the one-sided behavior of the zinc plate, both in air and in a vacuum, indicates electron emission from the illuminated metal.

Not all metals respond to all kinds of light in this manner. The most active metals (Periodic Table, Group I), including sodium, potassium, caesium, and their oxides and hydrides, respond readily even to visible light. The energy of the light is also an important factor. Visible light causes only the most active substances to emit electrons; ultra-

violet, which has more energy, is more effective, and X-ray still more s
The greater the frequency or energy of the light, the greater the speed of th
ejected electrons. More intense light causes more electrons to be emitte
in a given time. Therefore, to achieve the maximum effect, one woul
use an active substance irradiated by intense X-radiation.

The Photoelectric Cell. Use is made of this unusual phenomenon in the *photoelectric cell*, or "electric eye," as it is often called. There are many different types manufactured and used. In general the active material is enclosed in a glass or quartz bulb or tube, sometimes coated directly on the inner surface. The metal may be deposited, and if the oxide or hydride is desired, oxygen or hydrogen is introduced and reacts to form the compound. The tube may be of the vacuum type or it may be filled with an inert gas.

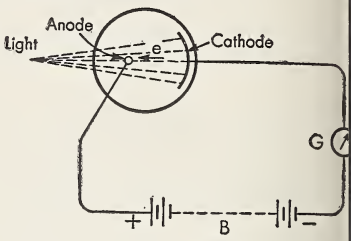


FIGURE 328. PHOTOELECTRIC CELL

Light causes metal or its compound emit electrons which move to the anod The flow of current in the circuit is ind cated by the galvanometer.

The active material serves as the cathode and is connected to the nega tive terminal of a battery *B* (Figure 328); a loop or grid (anode) is con nected to the positive terminal. When light strikes the cathode, elec trons are ejected and move under the influence of the potential to th anode, so that a small current flows. For a given frequency of light, thi current varies with the intensity of the light.

This small current may be amplified by a vacuum tube (see page 658) and may operate a relay, which is a very sensitive electromagnet wit many turns of wire. This relay in turn may open or close an electri switch and automatically control the operation of various electric appli ances. Light shines on the cell, for example, and the current flows acros the gap and on to an electromagnet which holds open the switch on a powe line circuit which operates a motor. When the beam is intercepted, th electromagnet releases the switch, which is closed by a spring, and th motor starts. Doors are opened and closed; safety devices, drinking foun tains, counting devices, and many other appliances are controlled by th electric eye. In connection with an amplifier and loudspeaker, it is use in the talking motion pictures. Television, transmission of photograph by wireless, devices for accurately matching colors in analytical chemistr — all employ some form of the photoelectric cell.

Another cell (photronic) gives what is called the *photovoltaic effect* Light shining on the sensitive material develops a small potential whic produces a current. Such cells require no battery and are used in th photographer's exposure meter. One such commercial cell employ cuprous oxide on copper.

The discovery and development of the electrochemical cell as a source f continuous direct current had far-reaching results aside from the practi- al uses of batteries today. Volta's announcement of his work was im- nediately a stimulus to more investigation, and the scientist now had a eal source of current. Huge batteries, some consisting of as many as wo thousand cells, were constructed. Ways were found of connecting hem to give higher voltage or greater current. In 1810, Sir Humphry)avy sent the current through the fused alkalies of sodium and potassium nd thus prepared these elements for the first time. In 1822, De la Rue nd Davy, using a hugh battery, developed the carbon arc, later used for ghting streets and in the electric arc furnace. Two other effects of the lectric current were discovered: one, that it heats substances through hich it passes; the other, that it produces magnetic effects.

More recent offsprings of the electric current are the cathode ray tube, -ray and its stimulus to the discovery of radioactivity, and the thermionic nd photoelectric effects. These discoveries not only have brought about reat and complete changes in science but also in our mode of life. But of ven greater importance, they have given us a more profound understand- ig of nature in the unification of matter and electricity. We shall discuss the next chapter the magnetic effect, important in itself, but of even reater significance because its discovery suggested to Faraday the idea hich led to his famous discovery of electromagnetic induction, the very undation of modern industry.

SUMMARY

. The electrical nature of matter and the atomic character of electricity have unified these two subjects.

. The electric current may be produced by chemical reaction in the various primary and storage cells. Electrons flow from a reducing agent through a conductor to an oxidizing agent.

. The electromotive series, a product of the oxidation-reduction cell, aids in the selection of oxidizing and reducing agents for the production of current.

. In storage cells the chemical reaction of discharge is reversed in the charging process. Safeguards must be taken in the maintenance of the lead battery.

. The Edison or thermionic effect, which is the emission of electrons from a hot wire, has great practical use in rectifiers and radio tubes.

. The photoelectric effect, which is the emission of electrons from metals or their compounds when exposed to light, is utilized in the electric eye.

. Both the thermionic and photoelectric effects confirm what was indicated by the cathode ray, chemical action and radioactivity; that is, electrons in motion constitute the electric current.

STUDY EXERCISES

1. Sum up all of the facts so far considered which may be regarded as points o evidence to prove, or, at least to indicate that: (*a*) the electric current is form of energy, (*b*) the electric current consists of electrons in motion.

2. Given a brief electromotive series with the element or ion in the reduced state in the column at left and in oxidized state in the column at right. If cells are made from each of the following combinations, which element or ion would be the source of electrons for the current (Column I)? Which element or ion would receive the electrons (Column II)?

Reduced	Oxidized
K	K^+
Mg	Mg^{++}
Zn	Zn^{++}
Fe	Fe^{++}
Ni	Ni^{++}
H_2	$2\ H^+$
Cu	Cu^{++}
$2\ I^-$	I_2
Ag	Ag^+
$2\ Cl^-$	Cl_2
Au	Au^+
$2\ F^-$	F_2

I	II		
.....	.....	Zn, Zn^{++}	Cu, Cu^{++}
.....	.....	Ag, Ag^+	Fe, Fe^{++}
.....	.....	H_2, $2\ H^+$	Ni, Ni^{++}
.....	.....	$2\ Cl^-$, Cl_2	Mg, Mg^{++}

Write the reaction taking place at each electrode for one of these combina tions, and indicate the reducing agent and the oxidizing agent.

3. Three types of cells or batteries in common use are listed. Answer in th column below each by a single word (which may be yes or no).

	Dry Cell	Lead Storage Battery	Edison Storage Battery
May it be recharged?			
Is it a "wet" cell?			
What is the source of electrons?			
What is the oxidizing agent? ...			
Does the cell deteriorate upon standing?			
What is maximum voltage for each cell?			
If a storage battery, how many cells are usually grouped together?			
Which has the lowest internal resistance?			
What is the electrolyte?			

4. Check the statement or phrase which correctly completes each sentence There may be more than one correct answer in each part.
   (*a*) The low internal resistance of the lead storage cell is due to:
   .... the high conductivity of lead.
   .... the nearness of the plates to each other.

.... the fast-moving hydrogen ion of the electrolyte.
.... the presence of lead sulfate.

(*b*) The disadvantages of the lead storage battery are:
.... it is heavy.
.... it delivers too high a current too quickly.
.... it deteriorates when not in use if discharged.

(*c*) The lead battery should:
.... not be overheated by external short-circuiting.
.... not be too rapidly charged near the end of a charging.
.... have the sulfuric acid replaced frequently.

5. Given a Leyden jar charged by an electrostatic machine and a voltaic pile or its modern counterpart — a dry or storage battery. Mark with an *A* if the statement below describes the former, with a *B* if the latter, and with a *C* if both.

.... High potential.
.... Discharge steady and may be repeated within limits.
.... Discharge violent and complete.
.... Is of practical use.
.... Electric energy is due to chemical reaction.
.... Requires expenditure of energy.
.... Yields electric current which may be used.

6. In comparing the Edison effect with the photoelectric effect, check in the proper space which is true of either or both phenomena.

	Edison Effect	Photoelectric Effect
(*a*) Electrons emitted from hot filament.	.....	.....
(*b*) Electrons emitted by metal or compound when exposed to light.	.....	.....
(*c*) Electrons move across gap in one direction only.	.....	.....
(*d*) Potential must be maintained between source of electrons and plate or loop which receives them.	.....	.....
(*e*) Some air or gas in tube or cell is essential.	.....	.....
(*f*) The conductor which receives the electrons must be connected to the positive terminal of a battery.	.....	.....
(*g*) The effect indicates the nature of the electric current.	.....	.....

7. Before each device listed below place the number corresponding to the phenomenon upon which it is based. In some cases more than one answer is required.

.... Radio tubes
.... Fleming valve or rectifier
.... Discharge of storage battery
.... Charging of storage battery
.... The electric eye

1. Photoelectric effect
2. Edison effect
3. Oxidation-reduction
4. Conversion of electric energy to chemical energy

.... The dry cell
.... The Daniell cell
.... X-ray tubes

5. Conversion of chemical energy to electric energy

8. Check each statement below which refers to or is associated with the movement of electrons:

.... Alpha particles
.... Beta particles
.... Edison effect
.... Positive rays
.... Electric current
.... Oxidation-reduction
.... Cathode rays
.... Photoelectric effect
.... Thermionic effect
.... Fleming valve

9. Write a brief statement to explain why discharge takes place in each of the following cases:
   (*a*) Hot wire negatively charged.
   (*b*) Negatively charged electroscope exposed to light.
   (*c*) Charged electroscope completely isolated.

10. Write a paragraph on each of the following topics:
    (*a*) The function of the grid in the thermionic tube.
    (*b*) A comparison of cathode ray discharge (Chapter 23) and the thermionic effect.
    (*c*) The practical consequences of the Edison effect.

FOR FURTHER READING

1. Lemon, H. B., *From Galileo to the Nuclear Age.*
   Chapter 30 is a good introduction to the photoelectric effect and thermionic emission.

2. Bragg, W. L., *Electricity.*
   In Chapter II the nature of the electric current, cells and batteries, the thermionic effect, and the photoelectric effect are considered.

3. Schlesinger, H. I., *General Chemistry.* New York: Longmans, Green and Company, 1937.
   In Chapter XXXIX the author discusses thoroughly and scientifically the principles underlying the operation of primary and storage cells. For the better prepared student.

4. Harrison, G. R., *Atoms in Action.*
   A strictly non-technical and thrilling account of some of the advances of modern science. Chapter VI tells of the "ransomed electron" in radio tubes and photoelectric cells. The entire book is well worth reading.

5. Stokley, James, *Electrons in Action.* New York: McGraw-Hill (Whittlesey House), 1946.
   The use of electrons in communications is treated in a simple and understandable manner. The photoelectric effect and the Edison effect are briefly explained in Chapter 3.

36

Magnetism—A Manifestation of Electricity

HE PHENOMENON OF MAGNETISM which today is so commonplace, yet so ttle understood, was known to the ancients even before electricity. Mag-ets are found in nature; electric charges had to be generated before their ffects could be observed. The natural magnets or lodestones, which are agments of an iron ore called *magnetite* (Fe_3O_4), attract pieces of iron and, hen suspended so that they are free to turn, orient themselves in approxi-ıately a north-south direction. Exactly when the first magnet was dis-ɔvered is not known, and much that is recorded is pure legend. Reference ɔ magnetism is made in the writings of Thales of Miletus; of Plato; of liny, who tells the story of the Cretan shepherd, Magnes, whose iron-pped crook was attracted by a natural magnet; of Lucretius, who refers ɔ the discovery of magnets in the province of Magnesia in Asia Minor. Vhatever the truth of such legends, the discoverer of magnetism was one ho possessed something made of iron, the history of which likewise fades to the past. Some knowledge of magnetism was, no doubt, discovered, st in the absence of written records, and rediscovered a number of times.

Unlike the electric charge, magnetism was early put to a practical use. ne Hindu writer mentions its use in surgery (600 B.C.). The Chinese ere the first to note the directive properties of the magnet, but there is no vidence that they used it for sea navigation. According to one account ey used a primitive magnetic compass on a land chariot nearly three ousand years ago. Authentic records indicate that Europeans were us-g the magnetic compass for sea navigation as early as the twelfth century ıd perhaps before. Thereafter the compass came into common use; but ch use promoted little understanding of magnetism. The first recorded perimental study of the properties of the magnet was made by Petrus ɛregrinus (1269), who shaped a spherical lodestone, located its poles, und that like poles repel and unlike poles attract, and broke a lodestone to pieces to find that each piece became a complete magnet.

Modern knowledge of magnetism and electricity is usually regarded as ginning with William Gilbert (1540–1603), physician to Queen Elizabeth d a great experimentalist. In his book, *De Magnete*, published in 1600,

were included the results of his researches on magnetism and electricity Previous work in these fields is reviewed, carefully organized, and set forth in scientific language. Like Peregrinus, Gilbert made a globular lodestone or *terrella*, which he regarded as a miniature earth and on which he mapped out the magnetic meridians and poles. He assumed coincidence of the earth's magnetic and geographic poles, which was not in accord with the report of Hudson in America that at 75° N. latitude the compass needle stood almost in a vertical direction.

Magnets Attract and Repel

Starting with our natural magnet, the lodestone, other magnets may be made. A piece of steel, like a watch spring or a needle, is stroked with the natural magnet and soon becomes magnetized itself. If this artificial magnet is suspended on a point or placed on a float in water so that it may turn freely, it orients itself just as the natural magnet does in a direction approximately north and south. This fact could be explained on the assumption that the magnet has only one pole, but experiment shows otherwise. If one end of a bar magnet is brought near the north-seeking end of our freely suspended magnetic needle, the latter moves. Again, when the same end of the bar magnet (Figure 329) is brought near the south-seeking pole of the needle, the latter moves in the opposite direction relatively to the bar magnet. Each magnet, therefore, has two poles, which we arbitrarily call the north-seeking or *north pole* and the south-seeking or *south pole.*

If we bring together two bar magnets with the like poles together, they repel each other; with opposite poles together, they attract each other. *Like magnetic poles repel and unlike magnetic poles attract each other.* The amount of attraction or repulsion varies, according to an induction made by Coulomb, directly with the strengths of the poles and inversely with the square of the distance between them. Mathematically, Coulomb's Law is expressed:

$$F(\text{orce}) = \frac{M_1(\text{agnetic pole strength}) \times M_2(\text{agnetic pole strength})}{d(\text{istance})^2}$$

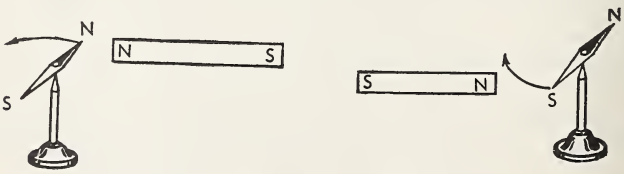


FIGURE 329

Each magnet has two poles. The north pole of a bar magnet repels one pole of the magnet needle but attracts the other pole.

where the poles are separated by a vacuum or by air. There are units expressing pole strength which may be established by experiment, but there is difficulty in making precise measurement of the distance between the center of action of the poles. Though the poles are somewhat near the ends of the magnet, these points are not definite. More important is the similarity between this law and the law of electrostatic action and that of gravitation.

Magnetic Substances

Magnets attract iron, cobalt, and nickel — three elements which are chemically and physically very closely related. Liquid oxygen is also attracted in somewhat the same way as iron. Other substances are not magnetic to such a great extent, but many, including the metals, show this property to a very slight degree. Bismuth displays a surprising kind of magnetic property — it is repelled. That a magnet can attract another piece of iron at a distance is in itself a remarkable fact and indicates that a zone or field of influence exists around the magnet. Obviously, the end of the nail or other iron object near the magnet is given the opposite kind of polarity, for it is attracted. Magnetization, like electrification, can therefore be brought about by *induction*. Strings of nails or tacks may be lifted by the magnet, each nail itself becoming magnetized and holding the one next to it. But the magnetism is not retained: as soon as the first nail is removed from the magnet, the others fall apart, and only a small amount, if any, of residual magnetism remains.

Only steel and certain alloys retain their magnetism so as to form so-called permanent magnets. Recently a number of alloys have been developed which are even more magnetic than iron, and some of them are made into powerful permanent magnets. One such alloy consists of copper, manganese, and aluminum, none of which metals is magnetic. Another, called *Alnico*, consisting of aluminum, nickel, and cobalt, lifts sixty times its own weight. Permanent magnets are used not only in navigators' and surveyors' compasses but in electrical measuring instruments, the telephone and telegraph, speedometers, and magnetos.

The Earth's Magnetism

The earth's magnetic field is of such character that we may imagine it to be due to an internal magnet about four thousand miles long, the south pole of which at present is just north and east of the Hudson Bay in 71° N. latitude and the north pole of which is south of Melbourne, Australia, in 70° S. latitude. But the cause of the earth's magnetism is not known. It has been observed, however, that sudden magnetic disturbances or storms usually accompany the appearance of sun spots and a prominent display of the aurora borealis. This suggests that the sun may emit rays of such a

nature as to ionize the earth's atmosphere and that the currents thus s up may be accompanied by magnetic effects.

It has been known since the fifteenth century that the magnetic compa does not in general point toward the true, or geographical, north po Columbus observed this fact and also that the variation from the tr north, known as the *magnetic declination*, changed from place to pla Knowledge of the magnetic declination at various points on the earth surface is of great importance to navigators, for though a modern ship ma carry a gyroscopic compass and may also make celestial observations, a ships carry a magnetic compass. Careful observations have been ma and are constantly being made from non-magnetic ships. The America ship *Carnegie*, operated by the Bureau of Terrestrial Magnetism, was co structed entirely of wood, bronze, and other non-magnetic metals, even the bolts, anchors, and cookstoves, to avoid any local attraction. Th ship made seven long voyages of observation over a period of fifteen yea until destroyed by an explosion and fire off Samoa in 1929. The Briti had under construction in 1939 a similar ship, the *Research*.

From the positions of the respective poles and the magnetic and celesti meridians, it is apparent that there are places on the earth with zero decli ation. The declination at New York (1930) is 11° West, so that there t compass needle points 11° West of true north; at Chicago it is 2° East, a

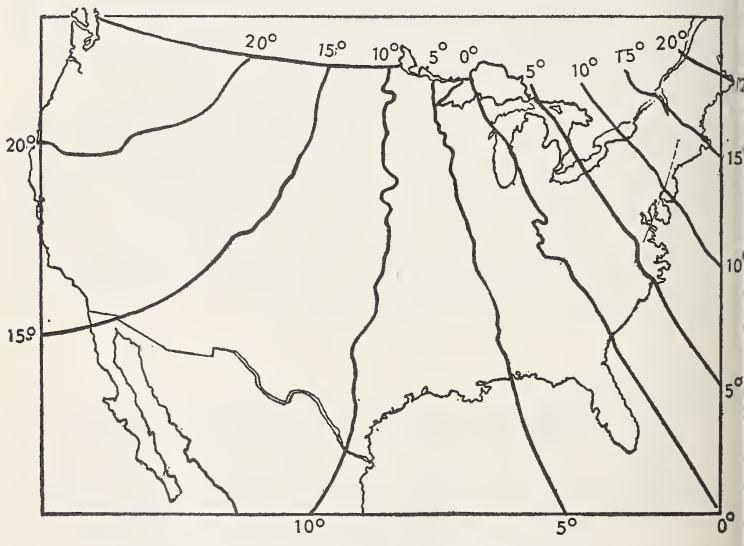


FIGURE 330. MAGNETIC MAP OF THE UNITED STATES (1935)

Lines are drawn through points of equal magnetic declination. The line of zero declin tion is just east of Chicago. (*Courtesy of U.S. Coast and Geodetic Survey*)

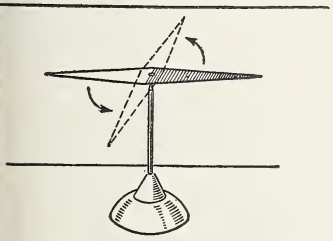
t San Francisco 18° East. A line of zero declination, then, must run hrough this country a little to the east of Chicago (Figure 330).

The form of the earth's magnetic field is continually changing; the mag-etic poles are shifting. There is a daily variation, and a much larger one xtending over a long period. A careful record of such variations is kept nd is referred to in studying old maps or surveys. Recently fragments of agnetite were uncovered in layers of sedimentary material laid down uring the ice ages. They were in conformity with the earth's magnetic eld at that time and lay in such a direction as to indicate that the northern agnetic pole was considerably west of its present position.

lagnetism from Electricity

And thus, for twenty-five hundred years magnetism and electricity were eveloped side by side, but as distinct subjects. They are unlike in some spects, as we shall see. Yet there are similarities: attraction and repul-on, a field effect, and the transfer to certain other bodies of their peculiar roperties. These similarities long led scientists to try to correlate the vo phenomena. The first real step was the observation, in the eighteenth ntury, that lightning flashes caused magnetization of iron. But it has en pointed out (Chapter 24) that man-made lightning discharged so rap-ly and at such high potentials that it was difficult to study its effects. he discovery of this vital relationship, just as the unification of matter d electricity, had to await the development of current electricity.

The years following Volta's announcement of a chemical source for ctric currents were very productive, perhaps more so than any period ce the Copernicus-Newton era. Among those who investigated the lationship between magnetism and electricity was Hans Christian rsted, a Danish physicist. Oersted was looking for some effect that uld show this relationship, and, although he did not know how to obtain it or what it would be, he was quite prepared to recognize it when by accident he hit upon the method. At the close of one of his lectures he placed a wire, carrying a current from a battery, above and parallel to a magnetic needle. The needle was deflected at right angles to the wire (Figure 331). He reversed the direction of the current, and the needle was deflected in the opposite direction. He changed the wire and found that the effect was independent of the material of the conductor.



GURE 331. OERSTED'S EXPERIMENT
The magnetic effect of current flowing in ire is shown by the deflection of a mag-ic needle.

This discovery, made in 1819, is of extreme importance. The electr current produces a magnetic effect; therefore, magnets which are suppli or excited by the electric current may be built. These may be powerful they may be delicate and sensitive, and they are easy to control. Moto generators, measuring instruments, the telegraph, the telephone, and hu dreds of other devices which we shall discuss in the next three chapters require electrically excited magnets (electromagnets).

In addition to the technological advances occasioned by this discove was the great stimulus to further investigation which yielded more disco eries and a greater understanding of magnetic and electrical phenomer In France a group of distinguished scientists, outstanding among whi was André Marie Ampère (1775–1836), made a careful study of Oerste work and clarified and extended it both experimentally and mathema cally. In America, Joseph Henry, and in England, Michael Faraday, ind pendently discovered the reverse effect — electricity from magnetis (Chapter 38). Some of Ampère's work may be better understood in co nection with the magnetic field.

The Magnetic Field

The region of influence around a magnet, like that around the earth o charged body, is a field of force. The gravitational field is different fr the electric field, and the magnetic field is different from either of the othe The magnetic field does not, for example, interfere with or exert any i fluence on the electric field at rest around a charged body. Faraday, w introduced the field concept, devised a way to interpret or represent Around a magnet the force exerted at each point may be measured both to magnitude and direction and may be so represented by so-called lines

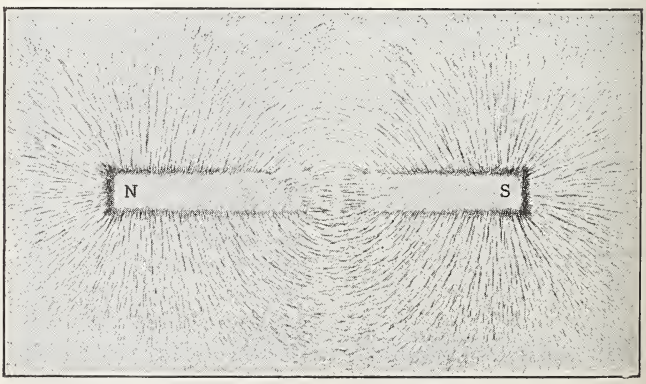


FIGURE 332. THE MAGNETIC FIELD AROUND A BAR MAGNET
(*Copyright, Houghton Mifflin Company*)

orce. In common practice we show the direction and to some extent the ntensity, but only in a plane, by placing magnetic compasses at different oints or, even more simply, by shaking iron filings on a piece of paper or lass placed over the magnet. In order to make the concept simpler, araday used the term "lines of force" and by convention regarded them s leaving the north or "positive" pole of a magnet and extending through the space around the magnet into the south or "negative" pole (Figure 332).

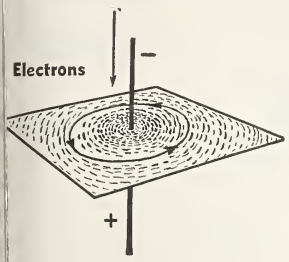


FIGURE 333

MAGNETIC FIELD AROUND A WIRE CARRYING CURRENT

Iron filings show lines of force, the rection of which is found by the left-nd rule.

If the single wire through which a current is flowing exerts a magnetic effect, then it must have around it a magnetic field. Iron filings sprinkled on a piece of paper show a field which encircles the wire in the direction indicated (Figure 333). If the wire is grasped by the *left hand* with the *thumb in the direction of the electron flow, or current, the fingers point in the direction of the lines of force around the wire.* When the wire is bent into a loop, we get the same effect but with the lines of force leaving one end of the loop and entering by the other (Figure 334, *a*). When the number of turns of wire increased, the field becomes stronger, and is then represented by more nes of force (Figure 334, *b*). A solenoid with many turns and with a ft iron core gives a much stronger field and is called an *electromagnet.* o Ampère we owe not only these discoveries but a rule for locating the les. Modernized, this rule is as follows: when the coil is gripped in e *left hand with the fingers around it pointing in the direction of electron w, the thumb points to the north pole* (see the figure below). ne field of the solenoid, or electromagnet, may now be compared with at of the bar form of the permanent magnet (Figure 335). They are ntical in character, which further demonstrates the close relationship

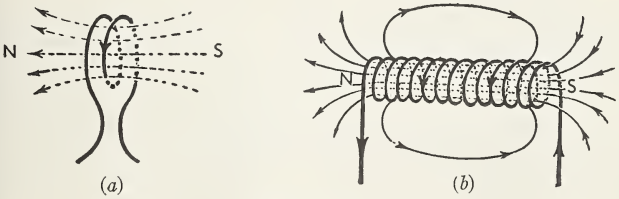


FIGURE 334

Lines of force leave and enter loop (a). The field is strengthened by increasing the number of turns of wire, and polarity is determined by use of the modernized Ampère rule.

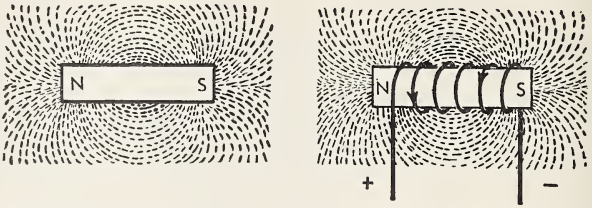


FIGURE 335. MAGNETIC FIELD OF A BAR MAGNET IS IDENTICAL WITH THAT OF AN ELECTROMAGNET

between electricity and magnetism and which suggests that *magnetism* ... *but an aspect or manifestation of electricity in motion.*

The Electromagnet

When a bar of soft iron is placed in the solenoid, the strength of th magnetic field created by the passage of the current through the wire greatly increased. The bar becomes magnetized by induction, concen trates the lines of force along its axis, and prevents leakage. A substanc with these properties is said to have a high permeability. Soft iron, whic is iron containing less than 0.1 per cent of carbon, is used, for it retain little of the magnetism after the current is shut off. Steel, which contain a higher percentage of carbon, retains its magnetism, and permanen magnets are made of it. There are many types of electromagnets fo a variety of purposes. Some are constructed with cores of special alloy for the telephone, telegraph, and radio; others with broad surface an powerful field for lifting great masses of iron. An electromagnet of th latter type attached to a crane is used for loading and unloading scrap iro and, in railroad work, lifting steel rails and placing them in position. Elec tromagnets are used in connection with conveyer belts to separate mag netic materials from ores or other materials. Safety devices, like th automatic circuit-breaker which opens the circuit when the current exceed the safe limit, and the elevator brake which stops the elevator when th current is cut off, are operated by electromagnets.

A very small electromagnet with many turns of insulated wire require but little current to produce a strong field. A flashlight cell supplies suff cient current to enable a small magnet to support a weight of more than hundred pounds. An interesting application of the electromagnet is in th removal of pieces of iron or steel from the eye or other parts of the body This technique was utilized by surgeons during the first World War even t remove shell fragments from the brain. We also read today of great mag nets which are used for experimental work with cosmic rays. In the cyclo tron, enormous magnets produce a powerful magnetic field which changes th direction of tiny projectiles, like deuterons, used to bombard atomic nuclei.

Rowland's Experiment

That the effect of the electric current on the compass needle is magnetic has been demonstrated by the identity of the fields produced by a permanent magnet and an electromagnet. That the electric current is necessary is shown by the utter absence of any effect of an electrostatic charge on the magnetic needle (Figure 336). Despite von Guericke's observation (page 648) and a demonstration by Wollaston that sparks from an electrostatic machine decompose water just as the electric current does, for a time there still existed some doubt of the relationship of static and current electricity.

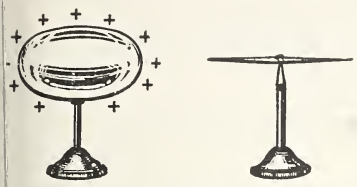


FIGURE 336
An electric charge at rest exerts no magnetic effect.

This doubt was removed by a brilliant experiment performed by H. A. Rowland of Johns Hopkins University. What Rowland did, in effect, was to whirl rapidly a small body which carried a static electric charge. A magnetic needle placed near it was deflected (Figure 337). Actually he rotated a glass disk on the outer part of which were stuck pieces of tinfoil all of which bore static charges. Greater speed of rotation produced a greater magnetic effect. When he reversed the direction of rotation, the needle was deflected in the opposite direction. *The moving charge is, in effect, an electric current.* Thus, Oersted's experiment, which demonstrated the interrelationship of magnetism and current electricity, provided the means by which Rowland unified the static charge and the electric current. These fundamental relationships which we shall use later relative to our discussion of the nature of light may be summarized:

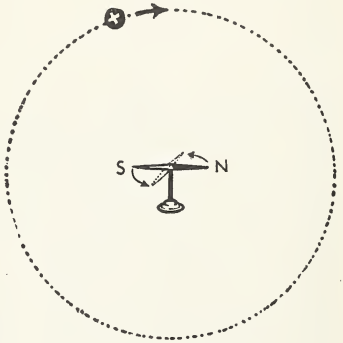


FIGURE 337
ROWLAND'S FAMOUS EXPERIMENT
A revolving charged body is in effect an electric current and creates a magnetic field.

1. A moving electric charge constitutes an electric current.
2. An electric current is always accompanied by a magnetic field.

What Causes Magnetism?

Certain experimental facts point to a theory of magnetism. A steel needle or a test tube of iron filings is magnetized by stroking with a magnet.

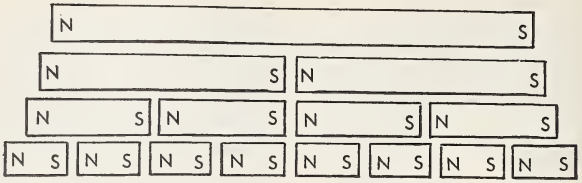


FIGURE 338

When a bar magnet is broken into two pieces, two complete magnets are produced. Th process may be carried out on smaller and smaller pieces with the same result.

We cannot look into the steel and see what has occurred, but we can se that the iron filings are definitely aligned. The steel needle is demag netized by hammering or heating, and the test tube of filings by shakin If the heated steel is allowed to cool in a magnetic field it regains its magn tism. Most significant is the fact that a magnet may be broken into tw pieces, but instead of getting a north pole on one and a south pole on th other fragment, we have two complete magnets (Figure 338). These tw magnets in turn may each be broken into two more, and the procedure ma be continued with the same results. Where does it end? We may co tinue in our imagination to divide the magnet into smaller and small fragments until finally we come to the molecule or atom as the fundament or unit magnet. This is precisely how Ampère theorized. His hypothes that the minute magnets of iron or other magnetic substances were due t electric currents within the atoms or molecules was not accepted at th time. The facts cited above, however, are in harmony with such an ide A piece of iron, for example, being composed of such elementary magne which, when unmagnetized, are arranged in small closed groups with th north pole of each near the south pole of its neighbor (Figure 339, *a*), ma be magnetized under the influence of a magnetic field. The units become so oriented that the north poles are all in one direction (Figure 339, *b*), but when they are heated the increased molecular activity destroys the alignment. In steel the intermolecular forces are greater, and hence the steel retains its magnetism more than does soft iron, in which molecular cohesive forces are not so great.

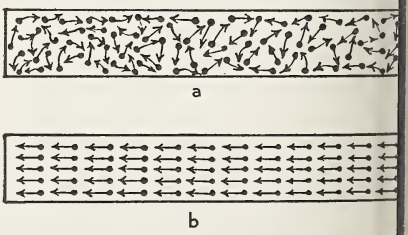


FIGURE 339. THEORY OF MAGNETISM

Atoms or atomic groups with revolving and spi ning electrons are magnets (a). When oriented a magnetic field, a bar of iron as a whole becom a magnet (b).

A moving electric charge, or current, is always accompanied by a magnetic field, as we have seen. Hence, in accordance with our present theory of atomic structure, the whirling electrons within the atoms may account for their magnetization. An outside magnetic field may orient the atoms or molecules, or even larger groups, in magnetic substances.

A similar explanation is given for the binding together of atoms or atomic nuclei, as in the case of hydrogen (H : H), by the sharing of electron pairs (Chapter 29). The electrons spinning in opposite directions may create magnetic effects which mutually attract.

Electrical Units

The electric current has thus far been spoken of as the flow of electrons through a conductor or across an open space. To an electrical engineer the term electric current has a quantitative meaning. It is the time rate of flow of the charge, or the quantity of charge passing a given point in one second:

$$I(\text{ntensity of electron flow, or current}) = \frac{Q(\text{uantity}) \text{ passing in } t \text{ seconds}}{t(\text{ime})}$$

$$I = \frac{Q}{t}$$

Electromagnetic Units

The magnetic effect of the current serves as the basis for another system of electrical units just as does the electrostatic charge (Chapter 23). Each system of units has its particular use. The fundamental charge, it may be recalled, was expressed in terms of the electrostatic unit (4.802×10^{-10} electrostatic units). The electromagnetic unit of current is that current which, upon flowing through a wire arc one centimeter long of a circle one centimeter in radius, exerts a force of one dyne on a unit magnetic pole placed at the center (Figure 340). This unit is called the *abampere*, but for practical purposes the *ampere*, which is one-tenth as large, is always used. Again we have a derived unit which is based upon mechanical effect and which may be expressed in terms of the three fundamental units of measurement. A sixty-watt lamp is lighted by a current of about one-half ampere flowing through it at one hundred and twenty volts. The storage battery used to turn the automobile starter may at times supply as high as fifty amperes for a very short time.

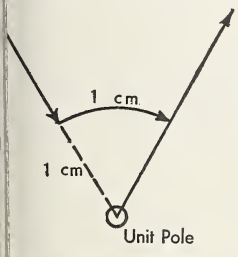


FIGURE 340

The electromagnetic unit of current is defined in terms of magnetic influence on a unit pole.

The practical unit of *quantity* of electricity, or electric charge, is th *coulomb*. It is equal to the charge borne by 6.3×10^{18} electrons. Th ampere, which is a coulomb per second, is therefore equal to the passage o 6.3×10^{18} electrons past a given point in one second.

$$I = \frac{Q}{t} \qquad \text{and} \qquad Q = It,$$

$$\text{or Amperes} = \frac{\text{coulombs}}{\text{seconds}} \text{ and Coulombs} = \text{amperes} \times \text{seconds.}$$

A lamp drawing a current of 0.5 amperes therefore consumes in one hou

$$60 \times 60 \text{ sec} \times 0.5 \text{ amperes} = 1800 \text{ ampere-seconds, or coulombs.}$$

The concept of *electric potential and potential difference* was introduced i Chapter 23 as the intensity factor for electricity and as being analogous t difference in water level or temperature, both of which are the result of th expenditure of work or energy and which respectively cause water and hea to flow to lower intensity levels. The potential difference is the facto which determines the direction of flow of electricity between two parts o a circuit. The practical unit of potential, the *volt*, is defined in terms o work. It is the potential difference existing between two points whe *one joule* of work is required to move a charge of *one coulomb* from on point to the other. Or

$$\text{one volt} = \text{one joule per coulomb, and}$$

$$\text{volts} = \frac{\text{joules}}{\text{coulombs.}}$$

A dry cell furnishes about 1.5 volts; ordinary lamps and standard hous equipment require one hundred and ten volts. Standard automobile ba teries supply six volts and a strong current.

To understand better the relationship between the various electrica units we may again compare the electric current with the flow of water in pipe. The total *quantity* of water which flows is expressed in *pounds* o gallons; the total *quantity* of electricity, in *coulombs*. The rate of flow o water is expressed in *pounds* or gallons *per second*; that of electricity or cu rent, in coulombs per seconds, or *amperes*. The *height* through which th water falls is expressed in *feet*; the *potential difference*, in *volts*. For wate the work done to give it potential energy is

$$\text{work} = \text{weight} \times \text{height, and}$$

$$\text{height} = \frac{\text{work}}{\text{weight.}}$$

For electricity the work done to establish a potential difference betwee two points is

$$\text{work} = \text{quantity of electricity} \times \text{potential difference,}$$

$$\text{and potential difference} = \frac{\text{work}}{\text{quantity of electricity.}}$$

TABLE 62. FLOW OF WATER AND OF ELECTRICITY COMPARED

	Flow of Water	Electric Current
Quantity	Pounds	Coulombs
Rate of flow	Pounds per sec	Coulombs per sec (amperes)
Level, or height through which it falls	Feet	Volts (potential difference)
Work done	Pounds × feet	Coulombs × volts
Level, or height through which it falls, in terms of work and quantity	$\frac{\text{Foot-pounds}}{\text{Pounds}} = \text{feet}$	$\frac{\text{Coulombs} \times \text{volts}}{\text{Coulombs}} = \text{volts}$

This analogy may be summed up in terms of the units, but we must not extend it too far. The units for running water bear the same relationship *to each other* as do the units for electricity; as, pounds per second or coulombs per second. Yet the pound does not have the same unit dimensions as does the coulomb. In the end, however, both enter into the expression for work. We should further note that in order to make the analogy simple we have used the pound weight which in the absolute system is *mg* (pound mass × acceleration of gravity).

The instruments used to measure current and potential difference will be described in the next chapter.

SUMMARY

1. Magnetism, the subject of much legend, was known to the ancients and there is some evidence of early use. Gilbert initiated the modern era for both magnetism and electricity.
2. Like magnetic poles repel and unlike poles attract each other with a force which is directly proportional to the product of their pole strengths and inversely proportional to the square of the distance between them (Coulomb's Law).

$$F = \frac{mm_1}{d^2}$$

3. Iron, cobalt, and nickel are the most magnetic substances. Other substances, including metals and liquid oxygen, show some magnetic property.
4. Magnetization may be brought about by induction. Steel and certain alloys retain this property to become permanent magnets.
5. The earth behaves as a huge magnet with the south pole near the Hudson Bay and the north pole south of Australia at 70° S. latitude. The earth's poles are constantly shifting. The deviation of the magnetic compass from true north is known as the magnetic declination.
6. Oersted made the great discovery that the electric current produces a magnetic field. Ampère developed electromagnetism.
7. The magnetic field is the zone of magnetic influence around a magnet. Identical fields may be produced by permanent magnets and by electromagnets.

8. The electromagnet, consisting of a coil of wire around a core of soft iron o of a special alloy, has many uses.
9. Rowland's experiment demonstrating that a rapidly moving charge was, i effect, an electric current and produced a magnetic field, makes possible th correlation of the three important phenomena, the static charge, the electri current, and magnetism.
10. The molecular theory of magnetism was originated by Ampère. The moder version holds that the magnetism is produced by moving electrons in th atoms. The atoms and molecules may be oriented by an external magneti field.
11. The magnetic effect of the electric current is the basis for the electromagneti system of electrical units.
12. The practical units of electricity are: of current or rate of flow, the ampere of quantity, the coulomb; of potential difference, the volt. They may b compared respectively to: rate of flow of water, quantity of water, water lev or pressure.

STUDY EXERCISES

1. Mark each of the statements as follows: *M* if true only of magnetism; *E* if tru only of static electricity; *B* if true of both; *N* if true of neither.
   .... Like poles or charges repel and unlike poles or charges attract eac other.
   .... Effect may be transferred to certain other bodies by induction.
   .... One kind of pole or charge cannot be developed without the other kin appearing simultaneously.
   .... One kind of pole or charge may be isolated from the other.
   .... Around a body which is electrically charged or magnetized is a fiel of force.
   .... The field at rest exerts an influence on a near-by magnet.
   .... The field at rest exerts influence on an electrically charged body.
   .... Phenomenon is due to transfer of electrons from one body or portio of a body to another.
   .... Phenomenon is thought to be due to spinning and revolution of elec trons around molecules or atoms.
   .... Effect may be produced by electricity in motion.
   .... Property is retained by body in contact with grounded conductor.
2. (*a*) Describe two methods by which a piece of steel may be magnetized How would it be demagnetized?
   (*b*) Write a *brief* discussion of the magnetic compass as an instrument of nav igation, pointing out the lack of coincidence between the earth's magneti and geographic poles and the need for data on magnetic declination a various points on the earth's surface.
3. Place in the space to the left the letter of the word or phrase which *best* com pletes the statement.
   (*a*) .... The first recorded experimental study of the earth's magnetism was made by: (*a*) Thales; (*b*) Gilbert; (*c*) Peregrinus; (*d*) Hudson

(*b*) .... Electromagnetism was discovered by: (*a*) Henry; (*b*) Faraday; (*c*) Volta; (*d*) Oersted.

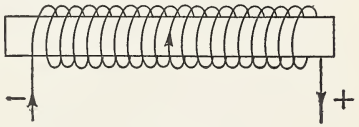
(*c*) .... The earth's south magnetic pole is located: (*a*) in 71° N. latitude near the Hudson Bay; (*b*) in 70° S. latitude south of Australia; (*c*) at the south geographic pole.

(*d*) .... Permanent magnets are used in: (*a*) magnetic lifting cranes; (*b*) the telephone; (*c*) the doorbell.

(*e*) .... An electromagnet consists of a coil of wire around a core of: (*a*) steel; (*b*) soft iron or a special alloy; (*c*) copper.

(*f*) .... When a permanent magnet is broken into two pieces the result is: (*a*) a magnet having only a north pole and another having only a south pole; (*b*) two complete magnets each with two poles; (*c*) demagnetization.

4. Below is a sketch of an electromagnet which consists of a coil of wire with a soft iron core. The direction of the electron current is indicated.



(*a*) Apply the left-hand rule to locate the north and south poles.

(*b*) Why is a coil of wire used instead of a heavy straight conductor?

(*c*) Why is the core used?

(*d*) How could the strength of the magnet be increased?

5. How does the field produced by a permanent bar magnet compare with that around an electromagnet of the same size and shape?

6. A magnet is broken into 100 pieces and yields 100 complete magnets. On the basis of Oersted's discovery, the present theory of atomic structure, and Rowland's experiment, extend the break-up in support of the theory that the molecule or atom is the ultimate magnet.

7. A magnet placed with its pole 4 cm from a nail exerts a force of 10 dynes on the nail. What force would it exert at a distance of 2 cm? At 8 cm?

8. (*a*) A current of two amperes flows through a circuit for three hours. What is the total quantity of electricity which flows past a given point in that time?

(*b*) Fifty joules of work are required to move a charge of 0.5 coulombs from one point in a circuit to another. What is the potential difference between the two points?

9. The fundamental unit of current in the electromagnetic system is the abampere.

(*a*) To how many of the practical units or amperes is it equal?

(*b*) From (*a*) we deduce that the fundamental unit of current is the passage of $10 \times 6.3 \times 10^{18}$ (the ampere) $= 6.3 \times 10^{19}$ electrons per second. Hence the fundamental electromagnetic quantity is 10 coulombs, or 6.3×10^{19} electrons. From Chapter 23 we recall that the electrostatic unit of charge was such that one electron $= 4.802 \times 10^{-10}$ electrostatic units. From these figures calculate how many electrostatic units there are in one electromagnetic unit.

10. On page 677 a tabular analogy between the electric current and the flow water is given. Prepare a similar table in which the electric current is co pared with the flow of heat.

FOR FURTHER READING

1. Lemon, H. B., *From Galileo to the Nuclear Age.*
Chapters 23, 24, and 25 have a good discussion of magnetism and the magne effect.
2. Taylor, L. W., *Physics, the Pioneer Science.*
Chapters 39, 42, and 43 contain an historical treatment of magnetism and excellent discussion of the magnetic effect of the electric current and electri units.
3. Morgan, A. P., *The Pageant of Electricity.*
Chapter II includes the early history of magnetism up to and including t first recorded use of the mariner's compass.
4. Wolf, A., *A History of Science, Technology and Philosophy in the Sixteen and Seventeenth Centuries.*
The outstanding developments in electricity and magnetism during the fi two centuries of the scientific era. Topics of special interest are the work of G bert and terrestrial magnetism. See especially Chapter XIII.
5. Einstein, Albert, and Leopold Infeld, *The Evolution of Physics.* Ne York: Simon and Schuster, 1938.
The superior student will find this scientific and philosophical discussion some of the great concepts of physics very stimulating. In portions of Chapte II and III the nature of electricity and magnetism and the field concept a presented from the standpoint of modern physics.

37

Electricity at Work

HE ELECTRIC CURRENT, whose character we now understand but whose roduction other than by chemical means we have yet to discuss, has three fects which determine its use and which make possible its study. One of ese effects, we have already learned, is magnetic. The electric current is ways accompanied by a magnetic field. Another is that the electric cur- nt, in passing through a wire, may have part of its energy converted into at. The third is found in the chemical changes caused by the passage of current through certain solutions or fused compounds. All have wide- read applications; all are useful to us every hour of the day. In our mes the operation of the vacuum cleaner, the electric washing machine, frigerator, clock, or fan — in fact, any device equipped with a motor — is e to the opposing magnetic fields produced by the current. The incan- scent lamp, the electric stove, toaster, and flatiron — all convert the ectric current directly into heat. Plated silverware, utensils of aluminum d of copper, even the books we read, are directly or indirectly the result chemical action brought about by electricity. We shall see first how such fects are employed in instruments for detecting and measuring the electric rrent, and second how this important form of energy is put to work to rform many tasks and to produce a multitude of useful things which add much to our comfort and efficiency.

e Moving Coil in Measuring Instruments

The magnetic compass in a loop of wire (Chapter 36) is essentially a easuring device of one type. A current flowing through the wire sets up a agnetic field which in turn is proportional to the current. There are easuring instruments of this type, but we shall limit our discussion to ose which employ the moving coil mounted or suspended in a fixed mag- tic field. The principle on which all such instruments operate is simply at like magnetic poles repel and unlike poles attract. A coil of wire is spended between the poles of a magnet (Figure 341, *a*). A current flowing rough the coil in the direction indicated creates another magnetic field, hich is perpendicular to that of the fixed magnets. Applying the left-

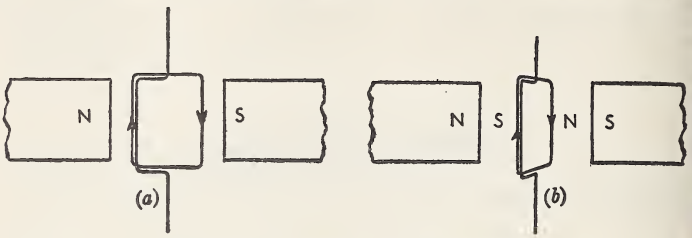


FIGURE 341. SIMPLE GALVANOMETER

Magnetic field which is established when current flows in coil interacts with the field due to magnets to turn coil.

hand rule, we see that its north pole is toward the reader, and the coil there fore swings to the right so that it is in the position shown in Figure 341, *b*. There it will remain as long as current flows, unless the twist of the suspen sion wire or some spring device returns it to its original position. The com mon *galvanometer* works precisely in this way. By using a large numbe of turns of fine wire, the magnetic effect of the current is greatly multiplied and a very sensitive instrument is the result. The turn of the coil may b observed by the reflection of a beam of light, by a tiny mirror attached t the suspension wire, upon a fixed scale.

More common are the voltmeters and ammeters which one sees in powe stations, in industrial plants where electricity is consumed, in laboratories and even in use for checking our storage batteries. In both instrument the moving coil which carries the current is mounted in jewel bearings be tween the poles of a strong permanent magnet bent in the shape of a horse shoe or of an arch. To insure a uniform magnetic field, soft iron pieces are placed on each pole of the magnet (Figure 342), and a soft iron core is mounted in the cylindrical space between. The lines of force between the poles of the magnet are thus uniformly distributed in the iron and in the small space between the core and the pole pieces. Around the cylinder turns the coil of wire through which the current flows by way of coiled springs placed at the top and bottom. These springs also serve to brake the coil uniformly and to return it to its position of rest. A pointer attached to the coil moves along a scale on which one may read

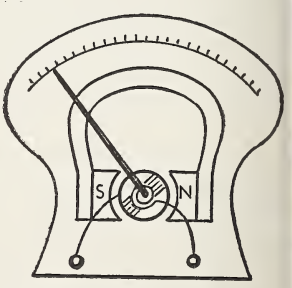


FIGURE 342. ELECTRICAL MEASURING INSTRUMENT

Coil through which current flows turns in magnetic field. These instruments operate on the same principle as the galvanometer.

olts, amperes, or fractions of these units. A current in the coil causes t to move around or to twist, for the same reason that the galvanometer oil moves. The twist, or better, the force producing the motion, increases ith the current.

Such an instrument may serve either as an ammeter or as a voltmeter. When used as an ammeter to measure the current, or the quantity of electricity passing in one second, it is placed directly in the circuit so that the urrent flows through the instrument. Instruments, lamps, or cells so rranged are said to be connected in *series*. The string of old-style Christmas-tree lights is arranged in series, and if one lamp burns out, all go out. However, all of the current does not pass through the coil of the instrument, or the coil is too delicate and too sensitive to permit large currents to pass hrough it without damage. Most of the current is shunted around the oil across the terminals (Figure 343, *a*). A small but definite fraction of the otal current passes through the coil *C*, and the scale is so calibrated that the otal current is registered. Again, the water analogy is helpful. If we ish to measure the quantity of water flowing through a pipe in a given me, we may divert a definite fraction — for example, one one-hundredth f it — through a meter (Figure 343, *b*). This is measured and multiplied y 100 on the meter scale, while 99 per cent of it flows through the main ipe. Both arrangements measure without appreciable obstruction to ther the flow of electricity or that of water.

The voltmeter, which measures the potential difference, or potential drop, etween two points in a circuit, is not placed directly in the circuit as is the mmeter. It is connected to the two points around and parallel to the portion of the circuit for which the potential drop is to be measured. A high sistance (*R* in Figure 344, *a*, a wire which resists the flow of current) is aced in series with the coil, so that very little of the current is diverted

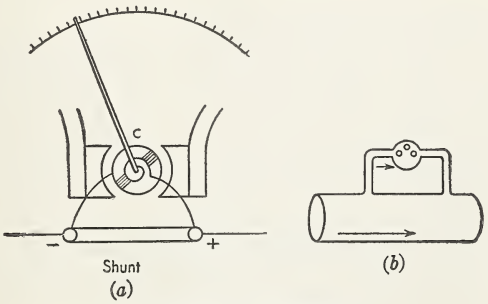


FIGURE 343. AMMETER

Measuring instrument connected in series but with most of current shunted around the licate moving coil C *compared with measurement of water flowing in pipe* (*b*) *by diversion a small but definite fraction of flow through the meter.*

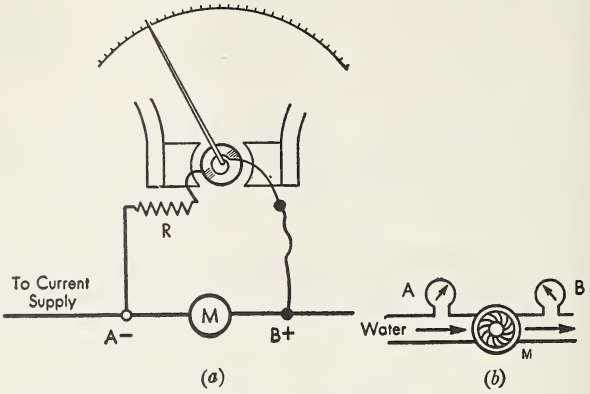


FIGURE 344. VOLTMETER

Measuring instrument connected in parallel but with heavy resistance in series. Litt current passes through the coil but the drop in potential around motor M is measured. Th drop in water pressure in passing through water turbine may likewise be noted by readin of meters.

through the instrument. To measure the potential drop caused by th work done by the current on a lamp or a motor M, the instrument is co nected in parallel with it at points A and B. Similarly, water pressures ar measured by pressure gauges, or manometers, placed in the water pipe a intervals (Figure 344, b) with none of the water flowing through the gaug The fall in pressure of the water occasioned by work which the water do may be found by reading the gauges A and B on the two sides of the wate motor or wheel M.

Mechanical Work by the Electric Current

The magnetic effect of the current may be used to do mechanical wor by precisely the same principle upon which the measuring instrument operate. The machine which makes this conversion is the *motor*. A ver simple direct-current motor may be made by mounting a coil of a few turn of wire on a metal core between the poles of a magnet. There is a magneti field between the poles, and when a current is sent through the coil of wir another magnetic field is established. The interaction of these two field which we observe as attractions and repulsions, causes the coil to rotate In Figure 345 (a) the current is flowing through the coil, or *armature*, in suc a direction (left-hand rule) that its poles are each attracted by the opposit poles of the fixed, or *field*, magnet toward which they are moving. Whe the south pole of the armature coil is just opposite to the north pole of th field magnet, and vice versa, the coil would stop except for the very handy

vitching device *c*, called the *commutator*, which at exactly the right moment auses the direction of the current in the coil to reverse. The polarity of ie armature also reverses, and the rotation continues, each of its poles ow being repelled by the like poles of the field magnet (Figure 345, *b*). fter a ninety-degree turn there is no change (Figure 345, *c*), except that e poles are now attracting instead of repelling. At every half-rotation e current in the armature is reversed. All this occurs quickly and autoatically, and even with the single coil and magnet we may have a rapid tation.

The commutator shown in the drawings and enlarged in Figure 345, *d* is a lit ring mounted on the armature. The two segments are insulated from ch other and each is connected to one end of the wire in the coil. Pressing ainst each of the two halves of the rotating commutator is a metal spring

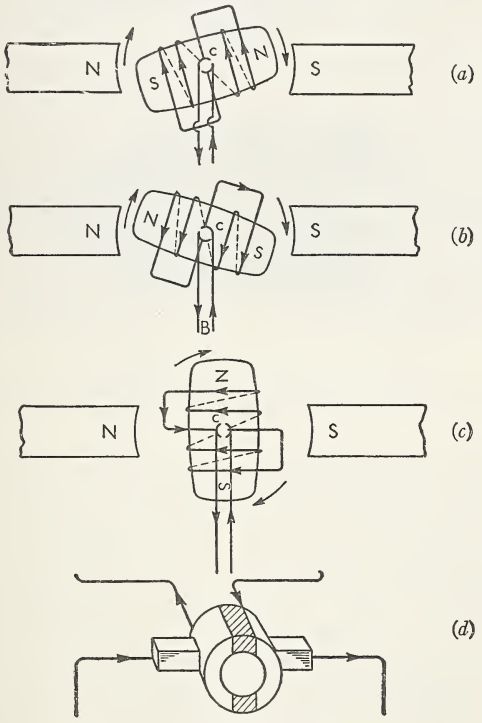


FIGURE 345. SIMPLE MOTOR

Interaction of magnetic field causes armature to rotate. Enlarged section of commutator with brushes is shown in diagram d.

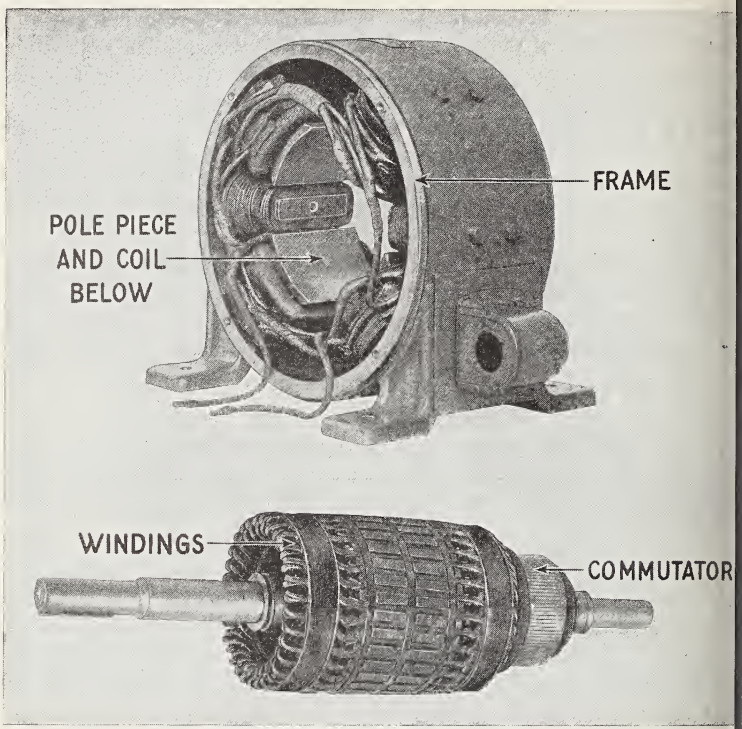


FIGURE 346. DIRECT CURRENT MOTOR
Showing field coils (above) and armature with commutator (below).
(Courtesy of General Electric Company)

strip called a *brush.* It is through the brushes that the current enters a leaves the armature by way of the commutator. At every half-rotati they exchange connections with the commutator segments.

The motor described above is an aid in understanding the operation commercial motors but would not do very much work and does not rota steadily. Motors for practical use are multiples of the simple motor. T magnetic field is stronger and more nearly uniform and is furnished electromagnets placed around the armature. These may receive the sa current as the armature (series wound) or only a part of it (shunt woun The armature consists of many turns of wire wound in slots lengthwise o drum which has an iron core. Instead of two halves to the commutat there are many segments, each pair in contact at a given time with one the coils (Figure 346). At any one moment one of the coils is receivi

e greatest amount of mechanical force. The rotation is without jerks, st as a six-cylinder automobile is much smoother in doing its work than e one-cylinder engine. The electric motor is a very efficient machine. ıere is very little loss through heat; in fact, very little heat is generated ıder normal conditions. The heat which is generated is due to the un- oidable electrical resistance of the coils. There is little friction, for the mature turns on bearings and the brushes are very smooth. The various nds of motors and their wide and extensive uses are described in the xt chapter.

onductors and Nonconductors

We have seen that a *conductor* of electricity is a substance that permits e current to pass through it without the application of a high potential. ıses become conductors only under conditions that speed up the motions d the impacts of ions and electrons — that is, in strong electric fields. ertain solutions and fused salts are conductors of a special type, for pas- ge of current through them brings about motions of ions and chemical anges. Metals are the best conductors, and may carry the current for indefinite length of time without any change other than a rise in tem- rature. In the atoms which constitute a crystal of a metal like copper silver, the outer, or valence, electrons are the ones which account for nductivity. These "free" electrons are in the interatomic spaces, and e average kinetic energy of a "free" electron is equal to that of the posi- ve ion in the metal. Some of these electrons move with extremely high locities, and when an electric field is set up in the metal — that is, when e wire is connected to a battery or source of current — their velocities are creased. *The drift or motion of these high-speed electrons in the direction the field constitutes the current in the wire.*

At ordinary temperatures the atoms of the metals are in motion which, ıile only that of vibration, is sufficient to bring about some collisions tween the high-speed electrons and the atoms. It is because of these llisions that the current heats the wire, which in turn may thus slightly nder the current or electron motion. The very best conductor, silver, not perfect. Copper, which is most used, and aluminum, which is being ore and more used, come next in order. If a metal is heated, its conduc- vity decreases; if it is cooled almost to absolute zero, it displays almost rfect conductivity, or superconductivity. This unusual property at ex- emely low temperatures is explained by our theory of conductivity. The oms are practically at rest, and the "free" electrons, some of which still ove with tremendous velocities, now have a free path and are able to ove considerable distances without collision. In fact, a current set up a conductor immersed in liquid hydrogen may continue for some time en after its source has been removed.

In a poor conductor the electron flow meets with some hindrance, which

may cause a great drop in potential or which may even stop the curren This electrical friction, which is called *resistance,* is just the opposite of co ductivity. Substances which offer high resistance are called *nonconductor* Sulfur, glass, rubber, mica, quartz, and shellac are nonconductors. A pe fect resistor or insulator does not exist.

Resistance

In actual practice we measure the resistance rather than its opposite ar mathematical reciprocal, the conductivity. The practical unit of resistan is the *ohm,* which is defined in terms of the unit of potential and of curren It is the resistance of such magnitude that a potential of *one volt* causes current of *one ampere* to flow through it. The resistance of a body is ind pendent of the current or voltage applied at a constant temperature. increases with the length of the body but diminishes with an increase in th cross sectional area. For example, copper, one of our best conductors, has relatively high resistance if drawn out in a very fine wire, but when ma into a short thick wire its resistance is very low.

Ohm's Law

It should be quite plain that the current passing through a conductor the form of a wire, as part of a circuit or lamp or cell, varies directly wi the voltage and inversely with the resistance. This relationship, which known as *Ohm's Law,* may be expressed by a single equation in which th practical units — ampere, volt, ohm — are used:

$$\frac{I\text{(ntensity) of electron flow, or Current} = E\text{(lectromotive) force, or potential difference}}{R\text{(esistance)}}$$

$$I \text{ (amperes)} = \frac{E \text{ (volts)}}{R \text{ (ohms)}}$$

This equation is very useful, for one may experimentally determine any o of the values by measuring the other two. For example, an electric lam circuit has inserted in it an ammeter and around the lamp a voltmete The ammeter reads 0.5 amperes and the voltmeter 100 volts. What is th resistance of the lamp? Substituting in the above equation, which is rea ranged to read

$$R = \frac{E}{I} = \frac{100 \text{ volts}}{0.5 \text{ amperes}} = 200 \text{ ohms},$$

we get the resistance of the lamp. It is by this method that the resistan may be measured.

Heat from Electricity

A perfect conductor would offer no resistance, and no work would ha to be done to maintain a flow of electricity. Actual substances, howeve

fer more or less resistance. The work or energy used to overcome this sistance is converted into heat. According to our theory of conductivity e electrons which constitute the current encounter and collide with atoms d molecules, which acquire more kinetic energy. The temperature, hich is dependent upon the average kinetic energy of these particles, is us raised.

The heating effect of the current is efficiently utilized for a number of actical purposes. The heat so generated is used for heating homes where e current is cheap, and for cooking; but the most important and extensive e is in the incandescent electric lamp. A filament for such a lamp must ve a very high melting point; and it must either have a high resistance the form of a fairly stout wire or, if a good conductor, must possess prop- ties which permit it to be drawn into very fine wires. The first filament ed was of platinum — uncovered and exposed to air. While platinum es not react with any of the substances in air, it has not a sufficiently gh melting point (1755° C.) to be an efficient converter of heat into light. low this temperature only a small fraction of the heat is converted into sible light. It is to Edison that we owe the carbon filament lamp. Car- n has an extremely high melting point (3500° C.), but burns readily in . Edison, who after considerable experiment found that he could obtain suitable carbon filament by heating a certain kind of bamboo in the ab- nce of air, enclosed this filament in a bulb and pumped out the air. At out 2000° C., or a little below, the efficiency of the lamp in terms of heat nverted into visible light was 1 per cent. At a few hundred degrees above is temperature the visible-light output is doubled, but the carbon soon sintegrates and the lamp "burns out." Lamps of this type, burning at out 2000° C., were in use for about twenty-five years.

Other possibilities were investigated. On looking through the list of the ements, one finds very few of them with a sufficiently high melting point. all the metals, tungsten has the highest melting point, 3350°, but it was ly after Coolidge, at the General Electric Company Laboratories, devel- ed a method of drawing it into a fine wire, that it came to be used. This etal offers a high resistance if in the form of a very fine filament. It is erated at a temperature of about 2800° and gives off whiter light with out five times the efficiency of carbon. In a vacuum it slowly subli- ates, blackening the bulb, and burns out. Lamps as used at present are erefore filled with an inactive gas, such as argon or nitrogen, and this eatly decreases the disintegration of the filament.

Certain alloys with a high resistance are used in electric irons, stoves, and okers. Chromel, which contains 61 per cent nickel, 23 per cent iron, and per cent chromium, and nichrome, which contains 75 per cent nickel, per cent iron, 11 per cent chromium, and 2 per cent manganese, are pical. The quantity of heat developed by an electric current depends on the resistance of the body through which it passes and upon the mag-

nitude of the current. By our definition of the volt (page 676), wo (Joules) = volts × coulombs. By Ohm's Law, E (volts) = I (curren × R (resistance); and by definition, Q (coulombs) = I (current) × (seconds). Hence,

$$W \text{ (joules)} = E \times Q = IR \times It = I^2Rt.$$

Or, since 4.18 joules = 1 calorie,

$$H\text{(eat) per second} = \frac{I^2R}{4.18} \text{ calories in 1 second}$$

In a lamp which requires two amperes and which has a resistance of fif ohms the heat generated is

$$H = \frac{I^2R}{4.18} = \frac{2^2 \times 50}{4.18} = 47.8 \text{ calories per second.}$$

These results assume that the circuit has a high resistance and that t electric energy is all converted into heat. Such a conversion is practical 100 per cent efficient, but this is not true of all heating devices. Carb filament lamps now used as a source of infra-red radiation (heat lamps) emit also considerable visible light.

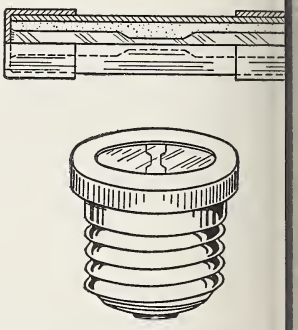


FIGURE 347. ELECTRIC FUSE

If conducting wires are overloaded with appliances, or are short-circuited, the excessive current which flows may cause overheating. To protect instruments and appliances and to eliminate the fire hazard, fuses are placed in the circuit. The fuse, which serves as a safety valve, bridges a gap in the circuit with an alloy which melts or "blows out" when the current exceeds a certain value. The temperature at which the fuse wire melts is such that there is no danger of fire from drops of the molten metal. But because an arc or flame is pr duced, it is necessary to enclose the fuse wire in an asbestos tube or in porcelain plug with a mica window (Figure 347). The size or kind of fu wire determines how much current it may carry without melting.

Ionic Compounds as Conductors

In Chapter 29 the conductivity of ionic compounds in water solution ar the resultant chemical changes were mentioned. Ionic compounds, it ma be recalled, consist of charged atoms or atomic groups which are called *io* and which are held together by the force of electrostatic attraction betwe unlike charges. In the solid or crystalline state the ions are arranged very definite patterns with respect to each other, and their motion is r

ricted to vibrations within certain limits. When the ionic compound is ssolved in a suitable liquid, like water, or fused, these ions are more free move about in random motion in accordance with the principles of the netic theory, and when placed in an electric field they move under its in- ience as do ions of gases (refer to Chapter 24). Sodium chloride, for exam- e, consists of sodium ions (Na^+) and chloride ions (Cl^-) arranged in a ystalline pattern. When dissolved in water, these ions break loose from e crystal and become surrounded by water molecules, which tend to keep em apart (page 541). The water-laden ions do not move as rapidly as e ions of a gas, for they are moving in a liquid medium and are not only ld back by the molecules of the water which they carry, but by frequent counters with molecules and ions. The conductivities of solutions or elts of various acids, bases, and salts depend upon the number of ions in a ven volume, the number of charges carried by each ion, and the speed th which the ions move. Strong acids are good conductors, for the drogen ion is small and moves faster than any other ion. On the other nd, the conductivity of solutions is different from that of metals. In utions ions move; in metals the free electrons move. In solutions the ctric current causes chemical changes to take place; in metals no chem- l changes are brought about by the electricity.

iemical Changes by Electric Currents

The nature of electrolysis, which is the effect produced by the passage of electric current through an ionic compound, may be best understood we first consider in a general way the changes which take place, and then ply the general principle to several specific cases of interest and of prac- al use. The simple electrolytic cell consists of a solution of an electrolyte, ich we represent by the generalized formula $A^+ B^-$, and of two electrodes, ually metallic. The electrodes are connected to a source of direct current, either a battery or a generator of current, which we shall discuss in the next chapter. The current source, or electron pump, sends electrons to the electrode (*cathode*) which is connected to the negative terminal (Figure 348) and removes them from the electrode (*anode*) which is connected to its positive terminal. When the circuit is closed, the ions move in accordance with the law of attraction and repulsion — the *positive* ions, or *cations*, toward the cathode; and the *negative* ions, or *anions*, toward the anode

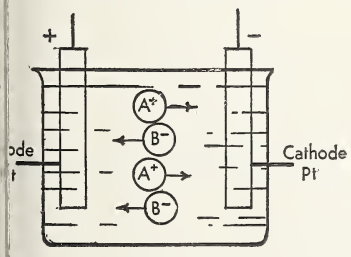


FIGURE 348
GENERALIZED ELECTRIC CELL
ons migrate as indicated, and oxidation es place at the anode; reduction, at the hode.

At the *anode*, negative ions give up their electrons and are *oxidized*; the cathode, ions receive electrons and are *reduced*. It is not always t migrating ions, to which the solution owes its conductivity, that are o dized and reduced. The electric current is thus used in the electrolytic c to bring about chemical reactions of oxidation-reduction. In the prima (dry) and secondary (storage) cells, it may be recalled, chemical reactio of oxidation-reduction are used to generate an electric current.

The Electrolytic Refining of Copper. Copper which is extracted from i ore by *metallurgical* processes contains a number of impurities, amo which are zinc, silver, and gold. These are removed, not only because of their value, but because copper of a high degree of purity is required for industrial use. The electrolysis is carried out between electrodes of copper, one of which is involved in the chemical reactions that take place. A slab of impure copper (Figure 349) serves as the anode, and a thin plate of pure copper as the cathode. Cupric-sulfate solution, with a small quantity of sulfuric acid, constitutes the electrolytic bath. The ions move in the directions indicated in the diagram — cupric ion to the cathode, and su fate ion to the anode. The anode is gradually consumed, for copper met gives up its electrons and is oxidized to the Cu^{++} ions. At the cathode t copper ion (Cu^{++}) receives electrons and is reduced to copper, which adher to the electrode. The cathode gradually increases in weight and size. T sum up the reactions:

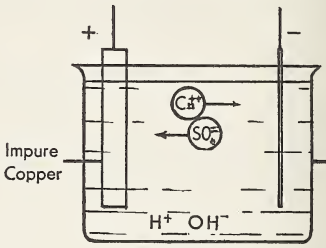


FIGURE 349
ELECTROLYTIC REFINING OF COPPER
Copper from the anode, which enters the sol tion as copper ion, is deposited at the catho minus impurities.

$$\text{At the anode, } Cu \longrightarrow Cu^{++} + 2e$$
$$\text{At the cathode, } Cu^{++} + 2e \longrightarrow Cu$$

The final effect of the electrolysis is to transfer copper from the anode t the cathode by way of the solution. The impurity, zinc, which is abov copper in the activity series, is more easily oxidized to the ion than is co per, for any voltage great enough to oxidize copper is capable of oxidizin zinc or any other metal above copper in activity. If the voltage is car fully regulated, zinc goes into solution as zinc ion and remains there, whi the less active silver and gold remain in the metallic state and fall to th bottom of the container. Copper of a purity of 99.95 per cent or more obtained by this method.

Electroplating. From the electrolysis just described we may formulate

eneral procedure — that is, the deposit of a metallic coating on an object metal or some other material by means of the electric current. Metals hich are easily corroded or worn are coated with less active ones. Iron is equently coated with copper, nickel, or silver. Tableware and other ob-cts made of cheaper alloys of nickel or other metals are plated with silver. hromium, which is used a great deal today, is applied in very thin layers, ut these are porous and do not give full protection to the metal beneath. ence, nickel is usually applied as a foundation for the chromium. In eneral, the object to be plated is placed in the electrolytic bath as the cathode, the metal with which it is to be plated is the anode, and the electrolyte is a salt of the same metal. For example, in silver plating (Figure 350) the tableware hung on a rack serves as the cathode, silver is the anode, and both are immersed in a solution containing silver ions.

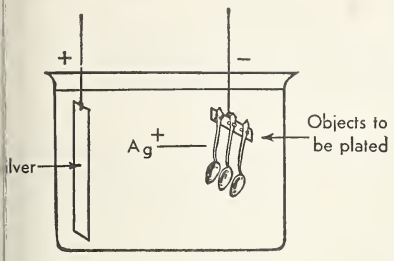


FIGURE 350. SILVER PLATING

A complex salt of silver is used as the electrolyte. lver from the anode enters the solution as silver n and is deposited on objects which serve as a thode.

In electrotyping plates for the printing of books, a wax mold is made by pressing a sheet of warm wax on the type, or "form," or the engraving. The wax mold or impression is coated with fine graphite (carbon), which is a nductor, and on this is electrolytically deposited a coating of copper or ckel. This duplicate is removed, or "stripped," from the mold and rein-rced with a thicker backing of electrotype metal. Such a plate will with-and many printings without becoming worn or defective.

raday's Law of Electrolysis

Faraday, the great experimenter, investigated electrolysis on a quanti-tive basis. He wished to find what relationship, if any, existed between e quantities of different elements liberated by identical quantities of ectricity. Electrodes were weighed before use and after the deposit of etal on them to ascertain the weight of metal deposited. Gases produced the electrolysis were collected and their volumes measured and their eights calculated. To insure the flow of identical quantities of electricity rough the various solutions of ionic compounds, he connected a number electrolytic cells in series — that is, the cathode of one to the anode of e next, and so on (Figure 351). The direct current was supplied by bat-ries. Faraday's results were embodied in his laws of electrolysis, which ere mentioned in Chapter 23 as the forerunner of the present ideas of the ture of electricity and matter. For elements of a valence of one, such as

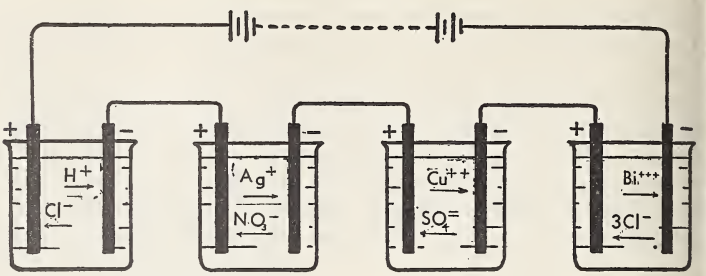


FIGURE 351. FARADAY'S LAW OF ELECTROLYSIS
Equal quantities of electricity discharge the same number of charges in each cell but not necessarily the same number of atoms.

silver, hydrogen, or chlorine, the quantities set free are in direct proportio to their atomic weights. For elements of a valence of more than one, th quantities set free are in proportion to the atomic weights divided by the respective valences.

From our knowledge of the electric current we conclude that the numbe of charges, each of which is neutralized at the anode by the loss of an elec tron or at the cathode by the gain of an electron, is the important factor i electrolysis. To discharge a single copper ion requires two electrons; to dis charge a hydrogen ion requires one. Hence, one hydrogen ion is equivalen to one-half a copper ion as a taker of electrons, and we get twice as many hydrogen atoms as copper atoms from the same quantity of electricity Faraday expressed this relationship by pointing out that equal quantities o electricity produce chemically equivalent amounts of elements. To liber ate the 107.88 grams of silver or 1.008 grams of hydrogen or 63.57 g/2 o copper requires 96,500 coulombs of electricity. Or, better, to furnis 6.02×10^{23} electrons requires 96,500 coulombs. One ampere flowing fo 96,500 seconds or one-half ampere flowing for $2 \times 96{,}500$ seconds ar merely different ways of supplying the 96,500 coulombs, or 1 *Faraday*, as i is called. The coulomb must therefore represent a charge of

$$\frac{6.02 \times 10^{23}}{96{,}500} = 6.2 \times 10^{18} \text{ electrons.}$$

(See Chapter 35.)

SUMMARY

1. The magnetic effect of the electric current and the principle of magneti repulsion and attraction are employed in these measuring instruments (*a*) the galvanometer is used to detect and measure small currents; (*b*) th ammeter, used to measure current, is connected in series, but most of th

current is shunted round its delicate coil; (*c*) the voltmeter, used to measure potential drop, is connected in parallel, but a large resistance permits only a small fraction of the current to pass through its coil.

. The electric motor operates on the same principle as the measuring instruments, but is equipped with a commutator to permit complete and continuous rotation. The practical D.C. motor is in construction a multiple of the simple one studied.

. Conductivity by metals is explained by the drift of free electrons through the solid metal; that of gases and non-metallic liquids by the movement of ions.

. Nonconductors, or insulators, are substances of low conductivity and high resistance such as glass, rubber, and sulfur.

. Work which is required to overcome resistance in a conductor is converted into heat. The heating effect of the current, which is due to impacts between the moving electrons of the current and atoms or molecules of the conductor, is utilized in the incandescent lamp, electric stoves, and the like.

. The resistance of a given material increases with its length and decreases with an increase in cross-sectional area. It is independent of the current or voltage applied.

. Ohm's Law, which may be expressed by the formula:

$$I \text{ (amperes)} = \frac{E \text{ (volts)}}{R \text{ (ohms)}}$$

is used to calculate any one of the three values when the other two are known.

. The heating effect, per second, of a current may be calculated by use of the equation:

$$H = \frac{I^2R}{4.18}$$

where I is the current in amperes and R the resistance in ohms.

The passage of a direct current through solutions of ionic compounds or through molten substances results in electrolysis which includes: (*a*) the ordered movement of ions and (*b*) chemical changes at each electrode — oxidation at the anode and reduction at the cathode.

Electrolytic methods are used in the production or purification of such metals as aluminum and copper and in electroplating and electrotyping.

Faraday's Law of Electrolysis points to a close relationship between matter and electricity and suggests that the latter is atomic in character.

STUDY EXERCISES

The functioning or operation of each one of the devices or processes listed below is due to one of three effects of the electric current. Mark with *M* if due to the magnetic effect; with *H* if due to the heating effect; with *C* if due to the chemical effect.

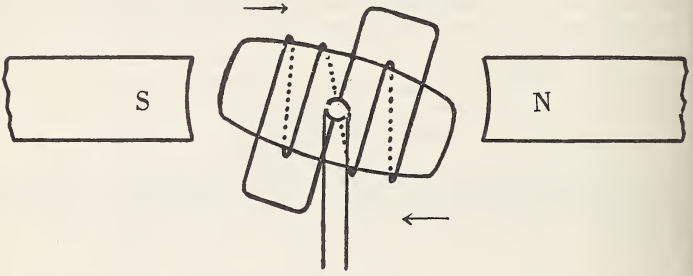
.... Electric lamp. .... Telegraph.
.... Electroplating. .... Electric clock.

.... Refrigerator. .... Galvanometer.
.... Vacuum cleaner. .... Radio tube.
.... Infra-red lamp. .... Spark plugs in automobile.

2. If the substance is a good conductor, mark *C* in the blank space; if a poo conductor or insulator, mark *N*.

.... copper	.... air	.... pure water
.... silver	.... glass	.... mica
.... sulfur	.... carbon	.... paper
.... rubber	.... amber	.... aluminum

3. Indicate by the letter *A* if statement is true of the ammeter; by *B* if true o the voltmeter.
.... Measures current.
.... Measures potential drop.
.... Is connected in series.
.... Has a resistance in series with it.
.... Is connected in parallel.
.... Has a shunt through whic most of the current is d verted.



4. The diagram represents a motor with field poles and the direction of rotatio shown. Mark each of the following parts: brushes (*B*), commutator (*C* armature (*A*). Indicate the direction of the electron current in the coil an in the wires leading to the brushes and the poles of the coil.
5. (*a*) Explain how a metal conducts electricity and why its conductivity de creases with a rise in temperature.
(*b*) Do the "free" electrons in a metal move with the same velocities as th atoms of the metal? On the basis of your answer explain the extremel high conductivity of a metal at a very low temperature.
6. Check each correct statement:
(*a*) The resistance of a given substance —
.... is proportional to the voltage applied to it.
.... increases with an increase in length.
.... increases with its cross-sectional area.
.... increases with an increase in temperature.
(*b*) The heat generated by a current in passage through a substance —
.... is due to the impact of the electrons on atoms.
.... increases with the resistance of the substance.
.... varies inversely with the square of the current.
.... is all converted to visible light above 2000° C.

(*c*) A lamp filament must —
.... have a low resistance when drawn to a fine filament.
.... have a very high melting point.
.... not vaporize easily.
.... not react with oxygen at white heat.

(*d*) In all cases of electrolysis —
.... ions migrate toward the electrodes carrying charges opposite to those on the ions.
.... oxidation takes place at the anode.
.... reduction takes place at the cathode.
.... the ions which migrate are always the ones which undergo oxidation or reduction.

7. Check in the appropriate blank space if the statement is true for either or both kinds of conductivity:

	Passage of current through metallic conductors	Passage of current through solution or melt of ionic substances
(*a*) Causes chemical change		
(*b*) Involves movement of ions		
(*c*) Involves movement or drift of electrons		
(*d*) Current meets with resistance		
(*e*) Direct current essential		
(*f*) Used to produce heat in some appliances		

8. Make a drawing of an electrolytic cell for plating a piece of iron with copper. Indicate what each electrode consists of; label each with its name and sign, and state what the electrolyte is. At which electrode does oxidation take place? At which electrode does reduction take place? Write equations for each.

9. How many electrons are required to reduce 100 atoms of silver ion to silver? How many copper ions (Cu^{++}) would be reduced by the same number of electrons? What law is illustrated by this relationship? Explain how this law suggested a relationship between matter and electricity and was the forerunner of our present theory of atomic structure.

10. How many amperes does a lamp with a resistance of 50 ohms draw on a 110-volt line?

11. An appliance whose resistance is 440 ohms draws 0.5 amperes. What is the voltage?

12. A 100-watt lamp draws 1 ampere on a 100-volt circuit. Calculate the resistance of the lamp and the number of calories of heat produced per second.

13. An electric stove unit on a 110-volt circuit draws 10 amperes. Calculate th resistance of the heating unit. How many calories are produced per second

14. A lamp on a 110-volt circuit draws 0.5 amperes. What is the resistance of th lamp? Calculate the number of calories of heat generated per secon assuming that all the electric energy is converted to heat.

FOR FURTHER READING

1. Bragg, W. L., *Electricity.*
In Chapter III the author reviews magnetism, electromagnetism, and its man applications in measuring instruments and describes and explains motors an the counterpart of the direct current motor, the dynamo, in simple language.

2. Lemon, H. B., *From Galileo to the Nuclear Age.*
The applications of electromagnets in measuring instruments and motors an the passage of current through solid and liquid conductors are the subjects of Cha ters 26 and 28. A very good explanation of Faraday's laws of electrolysis included.

3. Schlesinger, H. I., *General Chemistry.*
Chapters XIII and XIV contain a scientifically sound and a thorough modern interpretation of electrolysis.

4. Harrison, G. R., *Atoms in Action.*
Chapter V includes the development of various light sources including sodiu vapor and fluorescent lamps.

38

The Consequences of a "Useless" Discovery

WE HAVE SEEN that the electric current has served and is serving as a powerful tool in the hands of the research scientist. It has enabled him to investigate and to formulate brilliant workable theories concerning the nature of matter and electricity, and to unify static electricity, the electric current, and magnetism. The effects of the electric current permit its use for a great variety of purposes, so that it has become the most promising form of energy that we now have. In the home, in the factory, and on the farm it is bringing about marked changes in our way of life; in the hospital and clinic it aids in diagnosis and healing; throughout the world it serves as the messenger of man by flashing news, entertainment, and knowledge through wires and through space, even around the globe, in a fraction of a second. Today's widespread use of electricity, which will be multiplied many times in the next generation, would not be possible if we had to depend upon cells and batteries. These account for less than one per cent of the current now consumed. The great bulk of today's current is supplied by machines called *dynamos* or *generators*, which serve to convert mechanical energy into electrical energy. By visiting a power station in a large city or one of the great hydroelectric plants built by the government, we can see these enormous machines in operation. They are stationary, in that they rest upon concrete foundations, but they have moving parts which rotate swiftly. Whether steam or running water causes them to rotate, they produce a current of electricity when in motion. This current is conducted away from the generator and distributed in the city or across the country, sometimes over distances of hundreds of miles, to the consumer. But for the present we shall confine our discussion to the production rather than to the distribution of the current. How does a generator convert the mechanical energy of motion into electricity; or, in other words, how does it "work"?

Electric Current from Motion

Were we to examine such a generator while it is being assembled or taken apart, we should find little to enlighten us other than that it consists essentially of wires — many of them — and electromagnets. One or the other of

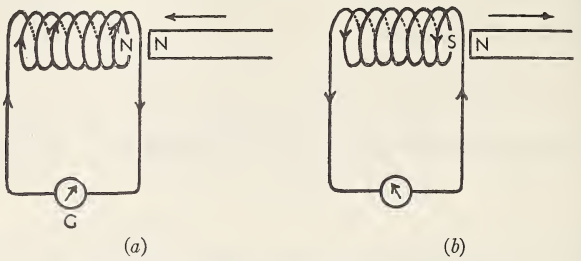


FIGURE 352. ELECTROMAGNETIC INDUCTION

A current flows in a coil of wire as a magnet is thrust into it. As the magnet is withdrawn the current flows in the opposite direction.

these moves when the machine is in operation. With a view to understan ing the principle underlying the production of electricity, we shall expe ment with a very simple home-made generator. This consists of a coil wire and a bar magnet. As the magnet is thrust into the coil (Figure 352, a current is generated in the latter. A galvanometer connected to the en of the coil — or a magnetic needle placed near the ends of the wire join in a loop — detects the current. The current so generated is only mome tary and exists only as long as the magnet is in motion. As the magnet withdrawn a current again flows in the coil but in the opposite directi (Figure 352, *b*). The magnet is now held stationary, and the coil thru over the magnet and then withdrawn. The results are the same (Figu 353). A piece of unmagnetized iron or steel produces no effect; if the en of the wire are not connected through the galvanometer or otherwise, effect is observed.

The current is developed only when there is motion of either the coil the magnet. They do not touch; therefore the magnetic field cutting acro the wire must cause the current by *induction*. This hypothesis may

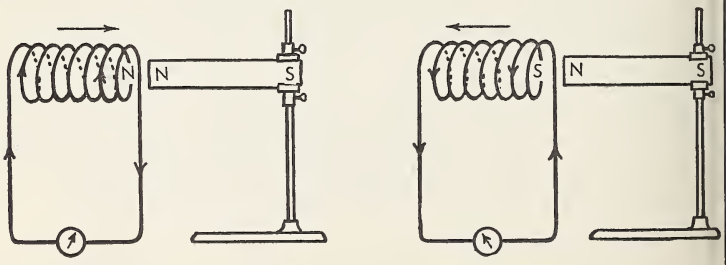


FIGURE 353. ELECTROMAGNETIC INDUCTION

As a coil is thrust over a stationary magnet current flows in the coil; as the coil is withdrawn current flows but in the opposite direction.

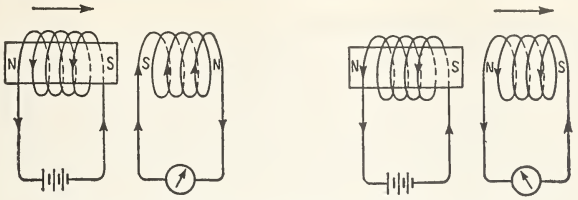


FIGURE 354. ELECTROMAGNETIC INDUCTION

An electromagnet may be substituted for the permanent magnet shown in the two preceding awings, with identical results. Motion of either coil or magnet induces current in the coil.

ırther tested in a number of ways. An electromagnet, which, as we have ɔen, possesses a magnetic field exactly like that of the permanent magnet, ıay be used. If either magnet or coil is moved (Figure 354), results ıentical with those described above are obtained. The electromagnet roduces a magnetic field only while a current is flowing in its coils. When ıe circuit of a battery is closed, a magnetic field builds up around the coil, ıd when the circuit is opened, the magnetic field collapses; in either case ıe field is changing — either expanding or contracting. Now we place our st coil, with the galvanometer, near the electromagnet, but move neither. he switch to the battery which supplies the electromagnet is closed (Figure 55, *b*); a current flows in the coil for a brief moment. The switch is ɔened; a current again is registered by the galvanometer but in the oppote direction. At each "make" and "break" of the circuit in the elecomagnet a current is induced in the coil. We conclude that when a ıagnetic field is cut by or cuts across a wire, a current is induced in the ire. It does not matter which is moved; and if the field is moved, it ıakes no difference whether this is done electrically — by the "make" ıd "break" — or mechanically — by moving the magnet. This phenomıon is known as *electromagnetic induction.*

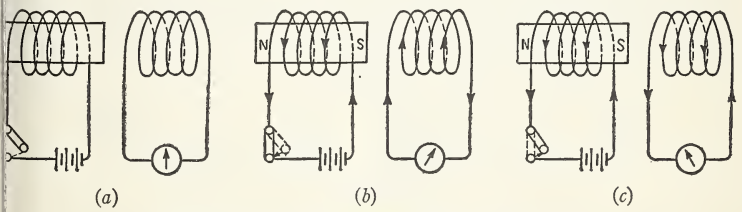


FIGURE 355. ELECTROMAGNETIC INDUCTION

Both electromagnet and coil are at rest. (a) With open circuit there is no effect; (b) when e circuit of the electromagnet is closed, a momentary current is induced in the coil; (c) when e switch is opened, a momentary current is induced but in the opposite direction.

The Discovery of Electromagnetic Induction

Electromagnetic induction was discovered in 1831 by Michael Farada (1791–1867). Prior to this outstanding addition to our knowledge of elec tricity and magnetism several important facts had been observed an studied. The first was the attraction and repulsion between static electri charges; second, the attraction and repulsion between magnetic poles third, the fact that the electric charge could be put in motion — that is that electric currents could be produced by chemical reaction; and fourth the magnetic effect of the electric current, which definitely wedded mag netism and electricity and showed the former to be an effect of electricity The last of these studies was made at just the right time to be taken u and carried forward by one of the greatest experimental scientists of a time — Faraday.

This great man began his career as a bookbinder's helper in London a the age of thirteen. He had very little formal education, but his employe impressed by his burning desire for knowledge and by his intelligence, sug gested that he read as much as possible so as "to know the insides as wel as the outsides of books." Faraday studied books on science, particularl chemistry and electricity, performing such experiments as he could affor to buy apparatus for. An opportunity was given him to attend a series o lectures delivered by Sir Humphry Davy at the Royal Institution. H took complete notes of these lectures, and having carefully bound them, h sent them to Davy with a request for employment. As a result he wa made Davy's laboratory assistant and later rose to be director of the labo ratory. There Faraday spent his life, a life rich in research and discovery i many fields. He studied liquefaction of gases and combustion, discovere benzene, prepared steel alloys which anticipated modern developments made new optical glass of high refractive power, and accomplished man other wonders; but he is best known for his work on electricity. The con cept of the electric and magnetic fields, the laws of electrolysis, and th wire-cage experiment (Chapter 23) are all his.

His greatest discovery was that of electromagnetic induction. If th electric current produces a magnetic field, reasoned Faraday, why not

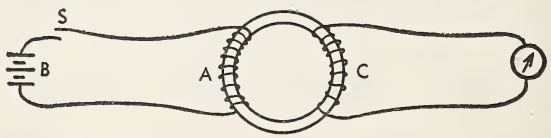


FIGURE 356. FARADAY'S EXPERIMENT BY MEANS OF WHICH HE DISCOVERED ELECTROMAGNETIC INDUCTION

Essentially the same as that shown in Figure 355, except for the iron ring which greatl increases the effect and is the forerunner of the modern transformer.

ciprocal effect? Why not use the magnetic field to produce an electric irrent? Magnets, placed near wires, did not give the expected effect. By ersistent experiment Faraday finally made the discovery that the magetic field must be in motion relative to the wire in which the current is duced. For does not the electric charge *in motion* produce a magnetic eld? Faraday's successful experiment, made in 1831, was essentially the me as that shown in Figure 355. He used an iron ring around which he rapped two coils of wire (Figure 356). One coil A was connected to a ttery B and had a switch S; the other, C, passed under a compass needle hich was in effect a galvanometer. At the make and break of the switch , momentary currents were induced in C, just as described in a previous ction. In the course of about ten days of actual experimental work Faray discovered and formulated the principles upon which modern electrical dustry is built. When asked, after a demonstration lecture, what was e practical value of his experiments, he is said to have replied, "Of what e is a newborn babe?" Thirty-one years later the first successful dynamo as built and used to supply current for arc-lighting. A method of procing an almost unlimited supply of electric current at a reasonable cost d been found.

e Direction of the Induced Current

In Figures 352 to 355 the direction of each current induced is indicated. is determined by a principle which is in harmony with the principle of nservation of energy. In nature all changes require work, for nature sists change. The principle which was first specifically applied to induced rrents by Lenz, bears his name. *The direction of an induced current is ch as to set up a magnetic field which opposes the motion producing it.* In gure 357 the current in the coil sets up a magnetic field whose north pole toward the north pole of the incoming bar magnet and tends to repel it. hen the bar magnet is being withdrawn, the current induced in the coil is the opposite direction. The magnetic field of the coil with the south end ward the retreating north pole of the bar magnet tends to hold it. The me rule is applicable whether permanent bar magnets or electromagnets e used and regardless of which one moves. It is likewise applicable, as we all see in the next section, to the current induced, or generated, by the namo.

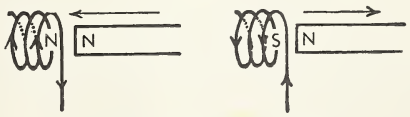


FIGURE 357. LENZ'S LAW

The current induced is in such direction as to set up fields which oppose the motion or ion producing it. The same conclusion may be arrived at by a study of Figures 352 to 355.

This principle also holds for even a single electromagnet, which may i duce a current in its own coils. When an electric circuit is broken, a spa is usually produced. The collapsing magnetic field cuts across the wir and thus induces a current. In accordance with Lenz's Law, the current in the direction which tends to maintain the field. When the circuit closed, the magnetic lines of force surge out and induce a current whic opposes the flow of the established current. This phenomenon of *sel induction* may be regarded as "electric inertia." Self-induction was di covered by a great American physicist, Joseph Henry (1797–1878), wh was working on electromagnetic induction at the same time as Farada and who independently made the same discovery.

The Generator

According to the principles we have discussed, a generator is a machin in which magnetic lines of force are cut across by or cut electrical condu tors. In the conductors the "free" electrons are thus put in motion and, the circuit is open, tend to pile up on one terminal of the wire and to lea the other. The electromotive force so created results in a current when th circuit is closed. Instead of plunging magnets in and out of coils or movin one to and fro relatively to the other, either the coil or the field is rotate Faraday, in fact, constructed a generator in which a copper disk was r tated between the poles of a horseshoe magnet (Figure 358). The constant current he generated was drawn from the disk by wires which were connected to the axle *A* and to the rim of the wheel by a metal spring, or "brush," *B*.

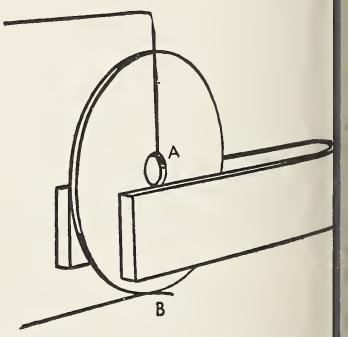


FIGURE 358. FARADAY'S GENERATO
A copper disk rotated between the poles of a horseshoe magnet yields a current.

The essential parts of a generator, whether it be a simple machine which we use for demonstration and study or a commercial dynamo, are:

1. *A magnetic field*, which is supplied by electromagnets. A single pair of electromagnets is used for the simple generator, and several pairs arranged in a circle for the commercial machine.

2. *A conductor*, in which the current is induced and which is called th *armature*. For our simple machine a loop of wire which rotates between th poles of the magnet is sufficient; but with a single loop of a few turns littl electromotive force or current would be generated. The commercial arma ture consists of many coils of wire wound lengthwise, usually on a cylinde or drum. The body, or *core*, is made of iron, and the wires are embedded i

rooves. In the direct-current generator, the *commutator* keeps the flow f current in one direction in the external circuit.

3. Collecting devices called *brushes*, which rub against the commutator n the direct-current generator and which enable the current to enter and ave the armature.

Our simple direct-current generator may now be assembled (Figure 359) - the electromagnets with north and south poles opposing, the armature *A* ith the coil of wire around an iron core, the commutator *C*, and the brushes . In position *a* the induced current is in such direction that the magnetic oles created by it are of the same polarity as those which they are ap- roaching. In position *c* the current in the coil has reversed, and its poles e now of opposite polarity to those which they are leaving. In both cases ie direction of the induced current is such as to oppose the motion pro- ucing it (Lenz's Law). The change in direction of the current comes as ie coil passes through its vertical position (position *b*). As it approaches ie vertical the top wires of the coil are cutting upward across the lines of

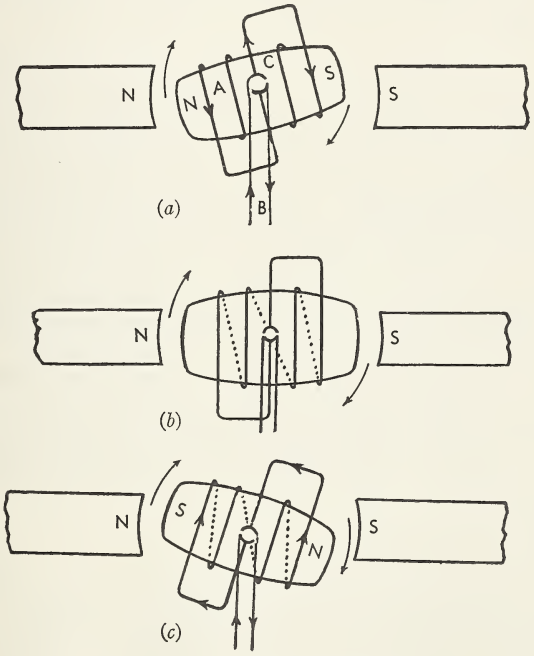


FIGURE 359. SIMPLE GENERATOR

Work is done to turn the armature against the opposing magnetic field. Most of the energy so expended appears as current.

force. At the vertical position it is moving in the direction of the lines of force, and, as it is cutting none, the induced current drops to zero. Beyond this point it cuts downward, and the induced current flows in the opposite direction. At 90° from position *b* it is cutting the maximum number of lines of force, and the induced electromotive force is greatest. Yet the current taken off by one brush and returned from the external circuit by the other is always in the same direction, for as the current in the coil changes its direction the brushes exchange their contacts with the two halves of the commutator.

Of great importance is the fact that work must be done in order to move the electrons through the wire of the armature or coil in which the current is induced. Just how these electrons are put in motion is not known. When the magnetic field sweeps across the wire or the wire cuts across the field portions of the lines of force may curl around the conductor and collapse into it. The energy of this portion of the field may appear as the induced current. Such a process is exactly the reverse of that described in Chapter 36, Figure 333, where current in passing through a conductor sets up a magnetic field.

From this description of the direct-current generator one can see that it is, in construction, identical with the direct-current motor (Chapter 37). In fact, the motor may be used as a generator. The current generated, however, flows in the opposite direction to that which would cause the armature to rotate in a given direction. Consequently, when used as a motor, the machine actually generates another current that opposes the current operating the motor. This electromotive counter-force accounts in part for the extremely low current which a motor draws when running at top speed without a load. When the motor is loaded to do work, the speed of rotation of the armature is less, the generator effect is correspondingly less, and consequently more current flows into it to do the extra work.

Commercial direct-current generators must produce greater current and voltage than our demonstration model. In other words, more lines of force must be cut in a given time. Obviously, this is done by increasing (1) the intensity of the magnetic field by means of more and stronger electromagnets, (2) the speed of rotation of the armature, and (3) the number of wires or conductors which comprise the armature and which cut the lines of force.

Why Use Direct Current?

We have discussed thus far direct current, which is that produced by all cells and batteries and by generators fitted with commutators. Though in actual practice direct current is commonly confined to certain uses, these are very definite. It is indispensable for electroplating, other electrochemical processes, and battery charging. Indeed, for a strong and steady magnetic field, necessary in lifting magnets and magnetic brakes, and even for

he magnetic field of the alternating-current generator, it is essential. Direct-current motors have several distinct advantages. They run at variable speeds, are easy to control, and start under a heavy load. They are used in elevators, electric locomotives, automobile starters, streetcars, and other machines which require a very high initial torque (turning force) at low speed and a controlled higher speed. One type of direct-current motor used for blowers and in machine shops runs at nearly the same speed with full load as with little or no load.

The great difficulty with direct current is the matter of transmission. All transmission lines, whether of copper or aluminum, offer a considerable amount of resistance, which, as we have noted, increases with the length of the conductor. There is, therefore, a serious drop in potential ($E = IR$) when the current is conveyed over any great distance. To step up the direct-current voltage for transmission and to step it down to lower voltages for local use would each time require a motor to operate a generator delivering the required voltage. The use of direct current on a large scale is therefore restricted to the central areas of large cities and to buildings or factories or other localities where it is generated on the premises.

Alternating Current

Referring again to the drawings of a simple dynamo (Figure 359), we observe that the direction of the induced current reverses with every half turn, or twice for every rotation of the armature. If we replace the commutator with solid rings of metal connected to each end of the coil and against which the brushes rub, we obtain an *alternating current*. Electrons rush back and forth, and these reversals of the current in the coil are carried to the external circuit. The sixty-cycle current which we use in our homes flows through the lamps or the motors in the electric clock or refrigerator, reverses, and then flows in the opposite direction, changing one hundred and twenty times, or making sixty complete cycles, every second. Most small alternating-current generators have, in common with those producing direct current, a rotating armature and a fixed field piece. In power plants large currents are generated at very high voltages. To build the insulation necessary for such high voltages and to avoid the use of sliding contacts, the large alternating-current generators are constructed with *stationary armatures* and *rotating field magnets* (Figure 360). The coils of the fixed armature or *stator* are placed in a ring framework. Within the stator is placed the rotating part of the machine (*rotor*) with the electromagnets arranged in a circle and projecting outward. Direct current is required for the electromagnets and is supplied by a separate direct-current generator or *exciter*. The alternating current induced in the armature, no parts of which move, is led directly to the switchboard.

Alternating-Current Motors. Alternating-current motors are, with one exception, structurally unlike direct-current motors. The *induction* motor,

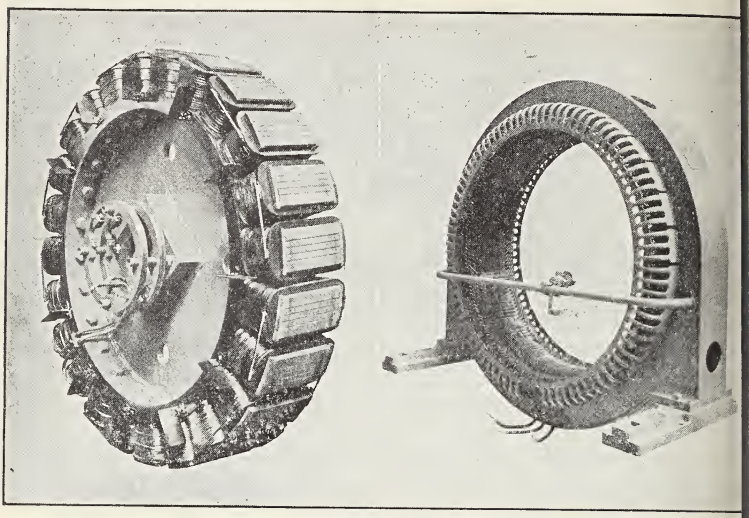


FIGURE 360. LOW SPEED A.C. GENERATOR PARTS WITH ROTOR (LEFT) AND STATOR (RIGHT)
(*Courtesy of General Electric Company*)

for example, uses a rotating field which may be obtained with alternatin current without mechanical rotation of the magnets. Within the rotatin magnetic field is mounted the moving part of the motor. The rotor con sists of heavy copper bars arranged in "squirrel cage" fashion and em bedded in an iron core. Lines of force cut the copper bars and strong cur rents are *induced* in them. The currents are in such a direction as to oppos the motion of the field by magnetic attraction and the rotor is pulle around with the field. The rotor never moves quite so fast as the field, fo then no lines of force would cut it. With a heavy load it moves mor slowly and the necessary larger currents are induced.

It should be noted that in the induction motor no rings or brushes ar necessary, for no current is supplied to the moving parts. The inductio motor is widely used in household appliances, such as refrigerators an fans, and in shops and factories. It may be modified to give a high startin torque with low current.

The *synchronous motor* consists of a stator which usually contains th field magnets supplied with direct current and a rotor or armature whic receives the alternating current. The armature pole pieces change thei polarity with the frequency of the alternating current and must rotate i step with the alternations and at a constant speed. This speed is the sam as or a multiple of that of the alternating-current generator which sup plies the current. The electric clock is operated by a simplified form of thi type of motor with a revolving permanent magnet.

The *universal motor* in which the field coils and armature are supplied by ıe same current (series wound) may be used with either direct or alternat-ıg current. The change in direction of the current changes the polarity of ɔth the armature coils and the field coils, so that the reaction between the vo fields is not changed. This type of motor, which in construction re-mbles the direct-current motor, is not very efficient and is rapidly going ıt of use except where small power is needed, as in sewing machines.

Vhy Use Alternating Current?

As indicated in our discussion of the restricted use of direct current, it is ıe alternating current that has the most extensive use. The reason for ıis is one of the chief reasons for using electric power at all — ease of ansmission. In order to send the electric current through conductors ver great distances without much loss, it must be at very high voltages. lternating current may be readily stepped up to extremely high voltages, nt over miles of high-tension transmission line, and then stepped down to wer voltages for home or local use. These changes are brought about by device known as a *transformer*. The principle of the transformer is that electromagnetic induction. In Figures 355 and 356 it was shown that ıe opening or closing of the direct circuit of an electromagnet induced a ırrent in a near-by coil. If, for the direct-current circuit which is opened ıd closed by a switch, we substitute alternating current and discard the vitch, we have a transformer. It has no moving parts save the growing ıd decaying magnetic field, which induces an alternating current in the ɔil across which it cuts.

The transformer, then, consists of two coils of wire which are wrapped round a continuous silicon-steel core (Figure 361). The core, which is uilt up of thin sheets insulated from each other, may be in the form of a ɔop or otherwise and forms a continuous magnetic circuit. For a step-up ansformer (Figure 361, *a*), the primary coil which receives the lower volt-

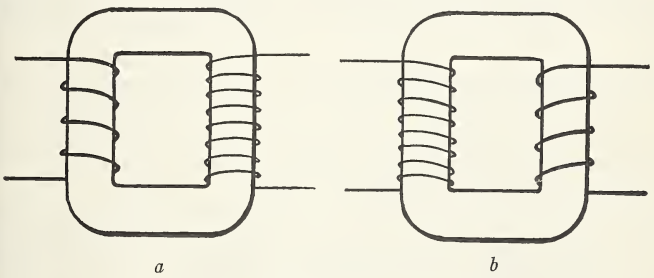


FIGURE 361. TRANSFORMERS

Working on the principle of electromagnetic induction, the transformer is used to step up) *or to step down (b) the voltage of alternating current.*

age alternating current must have fewer turns than the secondary in whi the high-voltage alternating current is induced. If we wish to multiply t voltage ten times, it is necessary to have ten times as many turns of wi in the secondary as in the primary. For the step-down transformer (Figu 361, *b*) the reverse is true. In both transformers the lines of force of the ma netic field sweep out and back across the secondary, and then repeat in t reverse direction, thus inducing another alternating current. The tw currents are entirely separate.

Here we have a means not only of transmitting the current but of chan ing the voltage for any use we may wish to put it to, whether it be for neon sign, a fluorescent lamp, a toy train, or an induction furnace. In t next chapter we shall see how the current is generated on a large scale, di tributed, and used.

SUMMARY

1. The electric current is induced in a wire when a magnetic field, produc either by a permanent magnet or an electromagnet, is cut by the wire or cu across the wire. This may be done mechanically, by motion, or electricall by the make and break of the circuit of an electromagnet. The phenomen is known as electromagnetic induction.
2. Electromagnetic induction was discovered by Joseph Henry in this count and by Michael Faraday in England. Faraday developed many of the i portant principles used in current generation.
3. The direction of an induced current is always such as to oppose the moti which produces it (Lenz's Law).
4. Self-induction, discovered by Henry, is known as "electric inertia" and is accordance with Lenz's Law.
5. A dynamo or generator consists of a magnetic field supplied by electroma nets, an armature in which the current is induced, and the collecting devic or brushes. A direct-current generator is equipped with a commutator.
6. Direct current is used in electrochemical industries and for variable spe motors with high starting torque. It cannot be efficiently transmitted ve far.
7. In an alternating-current generator there is no commutator. The curre reverses or alternates at a certain frequency. Large generators empl rotating field magnets (rotors) and a fixed armature (stator).
8. Most alternating-current motors utilize the rotating magnetic field, which obtained without moving field coils.
9. Alternating current is extensively used because its voltage may be stepp up to high voltages for more efficient transmission and stepped down to va ous usable voltages. The transformer, consisting of two independent co and with no moving parts, modifies the alternating-current voltage. It op ates by electromagnetic induction.

STUDY EXERCISES

1. Before each statement of discovery or achievement place the number corresponding to the name of the scientist associated with it.

.... Magnetic effect of the electric current.
.... Self-induction.
.... First electric "current" by transferring a charge through a conductor from one body to another.
.... Obtained current by chemical means but attributed it to "animal electricity."
.... Incandescent lamp with carbon filament.
.... Electromagnetic induction.
.... Theory of magnetism — rule for locating poles of electromagnet.
.... Lightning is electricity.
.... Current by chemical means.
.... Observed that light influences electric discharges.

1. Faraday
2. Edison
3. Hertz
4. Ampère
5. Oersted
6. Franklin
7. Henry
8. von Guericke
9. Volta
10. Galvani

2. An electric current is induced in a conductor by a magnetic field under certain circumstances. Check any of these if correct:

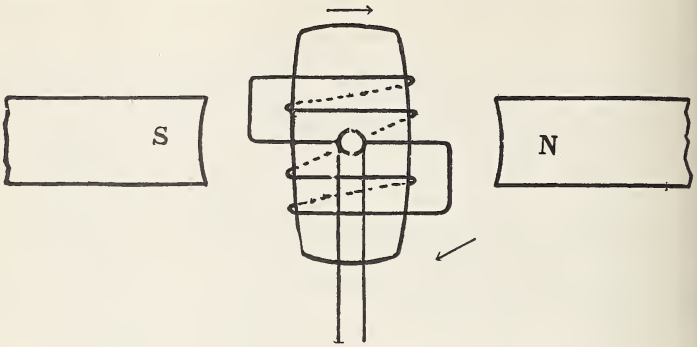
(*a*) .... The presence of the magnetic field and the conductor near each other but both at rest.
(*b*) .... Relative motion of either field or conductor in any direction.
(*c*) .... Motion of field and wire at same speed and in same direction.
(*d*) .... Mechanical motion of wire so that it cuts across the field.
(*e*) .... Mechanical motion of magnet so that field cuts across wire.
(*f*) .... Both magnet and wire at rest but field changing so as to surge back and forth across wire.

3. Make a general statement on electromagnetic induction, and describe how it may be demonstrated by the use of a straight wire, coil, or more complex armature winding, and a permanent magnet or electromagnet.

4. State Lenz's Law and show how it may be applied to all cases of electromagnetic induction (consult Figures 352 to 355) and to self-induction.

5. The diagram on page 712 represents a generator with field poles indicated.

(*a*) Is this machine for alternating or direct current? Explain.
(*b*) Could this machine be used as a motor?
(*c*) As a generator does it convert mechanical energy to electrical, or electrical energy to mechanical?
(*d*) Does the rotating coil do work, or must work be done to rotate it?
(*e*) Fill in the direction of the current in the wires and brush connections and indicate the poles of the coil.
(*f*) Name the three essential parts of a generator and indicate them on drawing.
(*g*) List three ways in which the voltage output may be increased.
(*a*) How would the generator shown on next page be modified in order to obtain alternating current?
(*b*) List the advantages of alternating current over direct current.



7. List the advantages of direct current over alternating current for some purposes.
8. Mark with *A* if device operates only on A.C.; with *D* if it operates only on D.C.; and with *E* if it operates on either.

.... Synchronous motor.	.... Series-wound motor.
.... Battery charger.	.... Streetcars.
.... Electrolytic cell.	.... Elevators.
.... Transformer.	.... Electric clock.
.... Lamp.	.... Neon sign.
.... Cathode ray tube.	.... Thermionic tube.
.... Induction motor.	.... Photoelectric cell.

9. Write in the blank space the letter corresponding to the one correct answer in each case:
   (*a*) .... In a dynamo the magnetic field is supplied by: (*a*) permanent magnets; (*b*) electromagnets fed by alternating current; (*c*) electromagnets fed by direct current.
   (*b*) .... Direct current is produced by a dynamo equipped: (*a*) with solid ring contacts from which the current is collected; (*b*) with a commutator from which the current is collected; (*c*) with a stator from which the induced current is drawn.
   (*c*) .... Direct-current motors are used for streetcars, electrically driven locomotives, and elevators because: (*a*) they run more smoothly; (*b*) they supply a greater starting torque; (*c*) no current is required for their moving parts.
10. (*a*) A step-up transformer has ten turns of wire in the primary coil, which receives a 110-volt current. How many turns in the secondary are required to step up the voltage to 550?
    (*b*) Make a drawing of a step-down transformer, label the parts, and explain the silicon-steel core. Which is used more in the home, the step-up or the step-down transformer?
    (*c*) The transformer operates on the principle of electromagnetic induction; yet no parts of it are in motion. Explain.

1. Discuss the life and work of Michael Faraday. Show how his discoveries have a great effect on our present mode of life.

FOR FURTHER READING

1. Eyring, C. F., *A Survey Course in Physics.*
Chapter XVI contains a review of the methods of generating electricity including electromagnetic induction.
2. Lemon, H. B., *From Galileo to the Nuclear Age.*
In Chapter 27 the author discusses in simple and clear language the phenomenon of electromagnetic induction and its use in the generator and transformer.
3. Taylor, L. W., *Physics, the Pioneer Science.*
Chapters 45 and 46 include good discussions on electromagnetic induction and dynamos.
4. Tilden, W. A., *Famous Chemists.*
Chapter XII gives a brief sketch of Michael Faraday's life and work.
5. Lenard, Philipp, *Great Men of Science.* Translated by H. Stafford Hatfield; New York: The Macmillan Company, 1933.
This book contains historical studies of the great investigators from Pythagoras to Heinrich Hertz. With many excellent portraits. Pages 247–263 contain a biographical sketch of Michael Faraday.

39

The Distribution and Use of Electric Power

THROUGH CONSIDERATION of simplified machines and apparatus we have studied the principles underlying the generation and use of electric current. We have seen that a procession of pioneer scientists — Franklin, Volta, Oersted, Faraday, Henry, Edison, and many others — has contributed to this knowledge and technological development. But despite the great progress which has been made and the electrical devices which we have at our command, we have just begun to use electricity and to realize its possibilities. In the total consumption of energy of all kinds the United States leads the world. Our per capita consumption is 60 per cent greater than that of Great Britain, and several hundred times that of China. Yet of the vast amount of energy which we consume, only a little more than one-tenth is electrical. The use of electricity has increased greatly in the last twenty years; in 1947 we consumed 60 per cent more than in 1941, and 180 per cent more than in 1929. The demands of the recent war brought about a rapid expansion in power production far beyond any peace-time expectations.

Behind the great expansion going on today is the story of large-scale production and distribution. Methods of generating electricity efficiently in large quantities have lowered the cost. Machines and devices utilize electricity so efficiently that they invite installation, and lead to the scrapping of less convenient and less efficient machines that utilize other forms of energy. The ease of transmission of electrical energy from large central power stations to the home, to the moving streetcar, to the factory, and across country, eliminates the need and expense of small individual power plants. Electricity is energy on tap — available at all times. We have, indeed, made great progress since Faraday performed his classic experiment a hundred and eighteen years ago. Although there is a strong contrast in both complexity and size between the simple apparatus used by Faraday and a modern generating unit, the latter operates on precisely the principles discovered by that great experimenter.

When we buy electricity, we buy energy which is delivered to us; and we

ay for it in terms of energy units. In this chapter we shall first introduce he concept of electric power and the units of power and of energy. We hall then consider the energy sources from which we draw our electric ower, and trace the distribution of electricity from this source to the onsumer.

aying the Bill

Electricity is billed to the consumer in terms of the kilowatt-hour, which is n energy (work) unit, but which is based upon the unit of power. Mechanal work and power have been discussed and expressed in terms of the funamental units of measurement. These units are no different when applied electricity, but we employ certain electrical units, amperes and volts, in lculating the electric energy, or work, and power. It has been shown Chapter 36) that

Work expressed in joules = coulombs × volts;
but since coulombs = amperes × seconds,
work (joules) = amperes × volts × seconds.

ower, it may be recalled (Chapter 21), is the time rate of doing work, or ie amount of work done in one second. The familiar unit in the British stem which was discussed is the horsepower. In the metric system the wer unit is the *watt*, named after James Watt, who played an important rt in the development of the steam engine. The watt is work done at ie rate of one joule per second; and

$$P(\text{ower}) \text{ in watts} = \frac{W(\text{ork}) \text{ in joules}}{t(\text{ime}) \text{ in seconds}} = \frac{\text{amperes} \times \text{volts} \times \cancel{\text{seconds}}}{\cancel{\text{seconds}}}; \text{ hence}$$

$$\text{watts} = \text{amperes} \times \text{volts}. \qquad (1)$$

nd since work = power × time, the work or energy of the electric current, hich is expressed in kilowatt-hours, may be obtained by use of the uation

$$\text{Kilowatt-hours} = \frac{\text{watts} \times \text{hours}}{1000}. \qquad (2)$$

quations (1) and (2) may be used in the solution of a number of problems:

(*a*) How many amperes does a 50-watt lamp draw on a 110-volt circuit? Since watts = volts × amperes,

$$\text{amperes} = \frac{\text{watts}}{\text{volts}} = \frac{50 \text{ watts}}{110 \text{ volts}} = 0.45 \text{ amperes}.$$

(*b*) A home uses ten lamps, each consuming electricity at the rate of fifty watts and each burning on the average seventy hours per month. What is the cost at three cents per kilowatt-hour?

$$\frac{10 \times 50 \text{ watts} \times 70 \text{ hours}}{1000} = 35 \text{ kilowatt-hours}; \; 35 \times 3 \text{ c} = \$1.05 \text{ cost}.$$

(*c*) An electric refrigerator is equipped with a one-fifth horsepower motor. A what rate does it consume electricity when running?

$$1 \text{ horsepower} = 746 \text{ watts}$$
$$\tfrac{1}{5} \times 746 \text{ watts} = 149 \text{ watts.}$$

The refrigerator when running consumes approximately the same elec tric power as three 50-watt lamps.

A 100-watt lamp is a more efficient light producer than two 50-wat lamps. That is, a greater percentage of the electrical energy is converte to visible light. Table 63 lists some common appliances with the averag or probable wattage of each.

TABLE 63. POWER CONSUMPTION FOR COMMON APPLIANCES

	Watts
Clocks	2
Coffee-makers, glass	550
Coffee percolators	350
Hotplates	1650
Lamps, flood	1000, 1500
Lamps, fluorescent (household)	15 and 20
Lamps, incandescent (household)	15–300
Phonographs	25
Radios	55–75
Razors	10
Ranges (connected load *)	7,000–20,000
Refrigerator (household)	170
Sewing machines	60–90
Toasters, automatic	1150
Toasters, non-automatic	450
Vacuum cleaners	375–600
Waffle irons	660–800
Washing machines	175

* Maximum power when all switches are turned on to full or high position.

TABLE 64. ESTIMATED ENERGY CONSUMPTION IN KILOWATT-HOURS PER MONTH FOR MOST COMMON HOUSEHOLD APPLIANCES

In the Home	Estimated Use	Kilowatt-hours/month
Cleaner	4 hr/mo	$1\frac{1}{2}$
Clock	1 month	$1\frac{1}{2}$
Coffee-maker	8 cups/day/mo	$4\frac{1}{2}$
Dishwasher	10 hrs/mo	4
Iron	12 hrs/mo	6
Ironer	12 hrs/mo	10
Mixer	3 hrs/mo	$\frac{3}{10}$
Radio (table model)	120 hrs/mo	$6\frac{2}{3}$
Range (family of 4)	1 month	92
Refrigerator (8 cu ft)	1 month	24
Roaster	40 hrs/mo	40
Toaster	6 slices/day/mo	$2\frac{2}{3}$
Washer	12 hrs/mo	2
Water heater (family of 4)	1 month	300

nergy Sources

The electric current and the electric discharge, other than lightning, is ot a natural form or source of energy. Since lightning has never been arnessed, we must draw upon other natural energy sources in order to erate the electric generator. Our demonstration generator is turned by ir most primitive source of energy — muscular. We turn it by hand. hose who cranked by hand the model T Ford automobile turned, among her things, the armature of a generator equipped with a permanent mag- t. This generator, known as a *magneto*, supplied the current for the igni- n system of the car until the engine started. But hand power is no nger used except for very special reasons. Admiral Byrd used an emer- ncy hand generator for his radio at his outpost in the Antarctic, and the my field radio is equipped with a hand-turned generator.

Other energy sources were discussed in Chapter 34. The wind, although ed sometimes in remote sections to operate battery-charging generators, not constant and does not offer concentrated power. Fuels, particularly al, petroleum, and gas, supply most of our energy of all kinds. Coal alone used to produce more than 60 per cent of our electric power. Running ater supplies practically all the rest of it.

oal-Burning Power Plants

The first commercial central power station for the generation of electric- was opened in New York City in 1882. Edison, after perfecting the in- ndescent lamp, built a constant-voltage dynamo which had an efficiency 90 per cent. The six dynamos in this plant were driven by reciprocating am engines and produced direct current. This current was of low volt- e and for reasons discussed in the preceding chapter could not be trans- tted more than a few blocks from the station. A few years later the first wer station generating alternating current was built at Greensburg, nnsylvania.

The modern power station which supplies current for large cities converts e chemical energy of coal into electricity by a long series of energy trans- rmations. Coal, which, as we have seen, obtained its energy from sun- ht some three hundred million years ago, is cheaper than the only other l which might compete with it — petroleum. But yet there are serious jections to its use for the generation of electricity. Coal must be mined d transported, often over great distances and at great cost. It is burned, d its heat of combustion is used to convert water to steam. The kinetic rgy of the steam molecules is converted to mechanical energy by a steam bine connected directly to the rotor of the generator (stages in the entire cess are illustrated in Figure 362). With every energy transformation chemical energy to heat, to steam, to mechanical energy, to electricity there is a loss of energy. Even with our most efficient methods of burn-

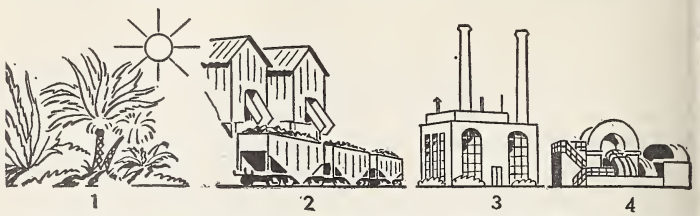


FIGURE 362. ENERGY TRANSFORMATIONS INVOLVED IN THE GENERATION OF ELECTRICITY BY USE OF COAL

Energy of sunlight captured millions of years ago, now in coal, is mined, transported, a burned, and the kinetic energy of steam is used to operate a turbine which turns the generat

ing the coal and of utilizing the steam, the energy loss is appalling large.

The coal is crushed to a powder and very completely burned under boile in which water is converted into steam. The steam, at temperatures high as 900° F. and at pressures up to 1800 pounds per square inch, ente the steam turbine. Here it is directed against curved blades on the ed of a wheel which is mounted on the shaft. From this section the stea exhausts into what is known as the reaction section, streaming through set of blades which resemble, in action, a windmill, then to the next set blades which is larger, and so on. These sets of blades are mounted on t shaft and become progressively larger as the steam expands and its pressu falls. The steam, after it has done its work, passes to the condenser, whe it is cooled and condensed to liquid water (Chapter 21).

The shaft of the turbine, which may make as many as 3600 revolutio per minute, is joined directly to the moving part of the alternatin current generator at the end of which is attached a small direct-cu rent generator, or exciter, which supplies current for the field magne of the rotor. In general, the generator voltage for the supply of cities 11,000 to 13,800 volts. Several turbine-generators may operate in o station, feeding their current to a common main line or busbar, into whi may also feed the current from other stations. From this line the curre may go directly to a substation, where the voltage is reduced by a ste down transformer to perhaps 2200 to 4000 volts (Figure 363). It is th distributed in this section of the city to smaller transformers, where it stepped down to 110 to 125 volts for home use. High-voltage alternati current may be stepped down and by means of a rotary converter chang to direct current at 420 to 600 volts for streetcar use.

For a high-tension system — that is, for long-distance transmission the generator voltage of possibly 22,000 to 33,000 volts is fed directly transformers which may step it up to 66,000 or 132,000 volts (Figure 364 The alternating-current system over a large section of the country, includi

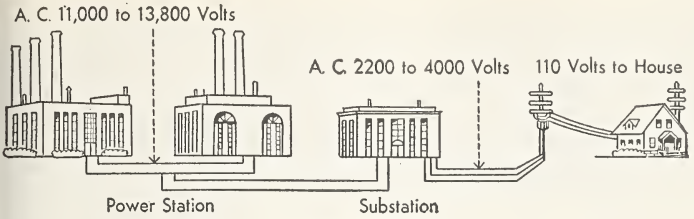


FIGURE 363. A TYPICAL CITY POWER SYSTEM

Electricity from power stations is fed to the main line, then to substation transformers here the voltage is reduced, and finally to pole transformers where it is reduced to usable ltages.

ties, may be connected in a network. Certain power houses are in oper- ion at all times, but others supply current to the network only where quired. The current may be distributed where needed for peak loads at rtain hours of the day or where, due to emergency situations, local power ants cannot handle the load.

ydroelectric Power Stations

Water power supplies at present about 35 per cent of the electricity sold the American public. Here and in other parts of the world vast amounts water power are going to waste. Fortunately, our government has cognized the great possibilities of this power source, which, unlike the windling supply of coal and other fuels, renews itself. Water runs down- ll because of the force of gravity but is evaporated by the energy of the n, falls as rain or snow, and the cycle continues to repeat itself. In order utilize the energy of running water and to have it available at all seasons, ms are built. The water is held back in a reservoir or lake which fills up,

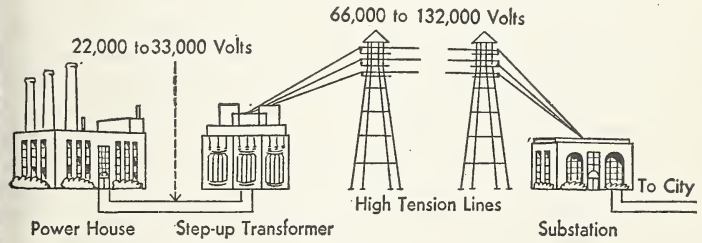


FIGURE 364. HIGH-TENSION DISTRIBUTION OF ELECTRICITY

High-voltage current from power stations is delivered to a step-up transformer, and the tage raised for long-distance transmission. Near the place of use its voltage is reduced in ps.

rising above the former level of the river. Thus the water behind the da has potential energy relative to the level to which it will fall when it is pe mitted to flow. This vertical difference in level, or the height throug which the water falls, is known as the *head*. It may vary from a few feet t several hundred feet.

The energy of the water is utilized in a water turbine, which operates o somewhat the same principle as the steam turbine. A jet of water may b directed against blades, paddles, or bowls, causing rotation of the wheel o which they are a part. Others work not by the direct impulse or impact o the water but by the kick-back, or reaction, of water leaving the blade Connected directly to the shaft of the water turbine is the electric gene ator. The large units of this are mounted vertically, so that the generato is above the water turbine. The speed of rotation of the water turbine nothing like as great as that of the steam turbine, but the efficiency is ver high, ranging from 85 to 93 per cent. Once the dam is built and the ma chinery installed, the cost of operation is relatively small, for the forces o nature supply the energy.

The water power of Niagara Falls has in part been harnessed and sup plies a number of American cities and a large industrial section with chea power. Vast hydroelectric power plants have been built by the Federa Government in several sections of the country. In the Tennessee Valle great dams control the flood waters and harness their enormous energy Industries, cities, and farms are supplied with power at low cost in an are which is almost as large as Great Britain and covers portions of seve states. At Hoover Dam the water of the Colorado River, operating at head of 510 feet, runs twelve 82,500-kilowatt generators housed in the dam Each generator requires a water turbine which delivers 115,000 horse power. Although not yet installed to its full capacity of 1,322,300 kilo watts, it is at present the largest operating plant in the world. Electri power is supplied to industries and to cities as far away as Los Angele The water held by the dam is utilized in part for irrigation projects.

In the Columbia River Basin, installation of hydroelectric generato has been made, but not to full capacity, at two dams, the Grand Coulee an one downstream at Bonneville. The Grand Coulee Dam (Figure 365) is th largest structure ever built by man, and behind it is the world's larges man-made lake. The lake site was formerly a fifty-mile long canyon fro which the dam gets its name. A few million years ago — which, geolog cally, is rather recently — a huge glacier diverted the course of the Colum bia River, forcing it to cut a new channel through the near-by rock. Afte the glacier receded, the river returned to its former course, leaving its rock channel as the trenchlike canyon known as the Grand Coulee. The dam supplies not only electric power, but water for irrigation, and will so regu late the level of water in the river as to aid navigation.

By the end of 1948 two 10,000 kilowatt and nine 108,000-kilowat

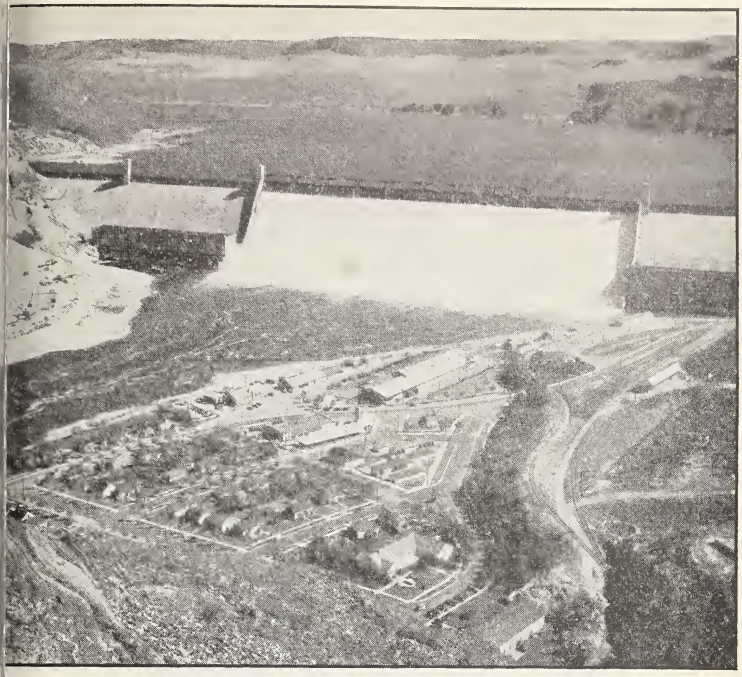


FIGURE 365. GRAND COULEE DAM

The elevation of the reservoir at the time the photograph was taken was 1277 feet and stream flow 65,000 cubic feet per second. (*Courtesy of Bureau of Reclamation*)

nerators had been installed. Three of these large units are capable of ghting New York City and Chicago combined, and exceed the joint out- ıt of Norris and Wilson Dams in the Tennessee Valley. During World ar II the war industries, including plants for the manufacture of alumi- ım and magnesium, consumed much of the output. The Government ans to complete by the end of 1951 the installation of nine more of the rge generating units, making the total output of the Grand Coulee plant 964,000 kilowatts. This power is supplied to the cities of the northwest, ıd is instrumental in the development of large industrial centers in the gion.

Water power does and will continue to produce about one-third of the ectricity sold in this country. New hydroelectric developments, such the St. Lawrence power and seaway project, will keep pace with the creased demand and the expansion in steam-operated plants. During e year ending December 31, 1947, we consumed approximately two ındred and seventy-three billion kilowatt-hours with a generating pacity of nearly sixty-six million kilowatts.

Moving Power Plants

Not all electric power plants are stationary — some are on wheels, som are afloat. Many ships — freighters, luxury liners, battleships, an smaller craft — are driven by electric motors, which are more quickl and easily controlled and reversed and which operate more smoothly tha Diesel or reciprocating steam engines. The electricity is, of course, ge erated by a Diesel engine (Figure 366) or steam turbine. Diesel-electr motive power has been adopted by some railroads and, while not yet i general use, is slowly replacing steam. Powerful Diesel engines to eac of which is directly coupled a direct-current dynamo furnish the electr power to drive motors which are installed on the axles of the locomotiv High speed, absence of smoke, and much cheaper operating costs, all fav this type of power over the steam locomotive. Passenger trains wit this kind of equipment are common today, and a number of railroad are now using powerful freight locomotives equipped with four 135 horsepower Diesel engines, four generators, and sixteen motors an capable of hauling more than three thousand tons of freight at a spee

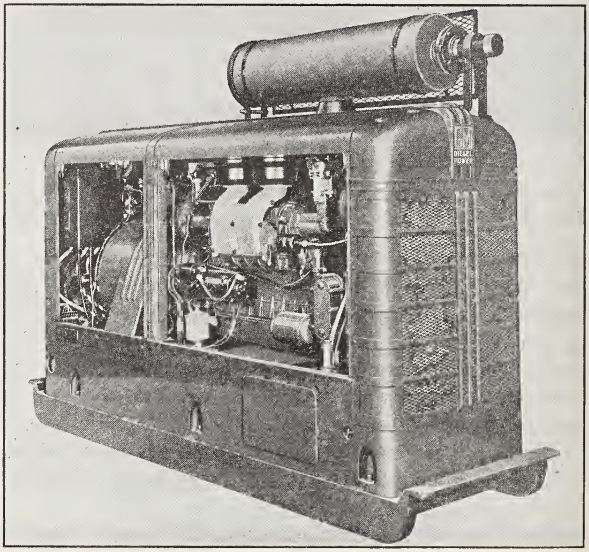


FIGURE 366. A PORTABLE SELF-CONTAINED POWER PLANT SUITABLE FOR USE AS A SOURCE OF ELECTRIC POWER AT POINTS REMOVED FROM POWER LINES, AS IN RURAL ELECTRIFICATION

An A.C. or a D.C. generator (left) is connected directly to the Diesel engine. (*Courtesy of General Motors*)

seventy-five miles per hour. That these trains are propelled by an ectric motor instead of by direct use of Diesel power is due to the lack of proper clutch system which will stand up under the terrific force required start the train. In order for the Diesel engine to develop enough power move the train, it must burn sufficient fuel and must therefore run at a ry high speed. To transmit this power directly to the axle or driving echanism of the locomotive would require an involved system of gears th low speed for starting and higher speeds for pick-up and running. The e of electricity permits a fairly simple solution of the problem. At the art both the Diesel engine and the generator armatures are running at full eed. But unless the armature is turning in a magnetic field no current operate the motors is being generated. Hence the operating power is ntrolled not by gears but by a regulation of the field current, that is, the rrent which supplies the magnetic field for the generator. As this current increased, the field strength and therefore the current which is induced generated and which operates the driving motors is increased; as the d current is decreased, less current is generated for the motors, and the omotive may slow up and be brought to a stop.

Nor are moving power plants limited to trains and boats. Every auto- bile and airplane is equipped with a small electric power plant. There a generator driven by the engine which delivers current only when the gine is running. A storage battery, charged by the generator, takes care starting and is a part of the ignition system. A spark coil steps up the tage for the spark plugs which fire the fuel in the cylinder at the right ment. From the current we get and use all the effects of electricity — ting for the firing and the lights, chemical energy for charging the bat- y, and magnetic flux for the induction, or spark coil.

ctricity and Our Mode of Life

It is easy to imagine what would occur if we were suddenly deprived of use of electricity. Our material way of life would slip back sixty or enty-five years or more. For transportation we should have to go back steam and to the horse and buggy. For lighting we should have to use jets or oil lamps or candles. The ice box would be filled by the iceman soon as the ice plant converted all its pumps and machinery to steam wer. For communication we should have to depend upon the postman irely — letters carried by train; no wireless, no radio, telegraph, or ephone. Our army and navy signal corps would be dependent on the naphore. In medicine there would be no X-ray for diagnosis or for atment. Operations in which inflammable anesthetics like ether and ylene are employed would be extremely hazardous with oil or gas light- . Industries would again turn to steam power and become more cen- lized in large units, and our already too large cities would become larger. ral sections would become more primitive and isolated without the

automobile and the good roads it brings and without small industrie supplied by easily transmitted electric power.

Fortunately, such events are not likely to happen at all, except throug some temporary misfortune. On the contrary, we have noted the grea expansion in the generation and use of electricity. Yet such expansion an use has been limited to our present total resources of water power and fue Unless some new energy source is made available either as a prime sourc for the generation of electricity or for direct use, we may reach a limit t our power facilities. Electricity, it may be recalled, was in the doldrum during the eighteenth century until rescued by the discoveries of Volta Our energy production could ultimately reach a similar impasse as a con sequence of the exhaustion of available present resources without th development of sufficient renewable energy sources like running water o the utilization of entirely new sources. Solar energy has possibilities. I tropical and semi-tropical climates the difference in temperature betwee ocean water on the surface and water at a depth has thermodynami possibilities. A most revolutionary event, the discovery of a means o converting matter into energy, has promising industrial implication Nuclear energy (see Chapter 27) made it possible to devastate Hiroshim with a single bomb. But the engines of peace also operate on energy Modern science is confident that nuclear energy will be available for man of the vital tasks of a modern society in a comparatively few years — per haps less than a generation. The wise and proper use of nuclear energ represents one of the greatest challenges ever faced by man.

For the immediate future we need a number of improvements in ou present methods of generating and distributing electrical energy. Firs we need greater efficiency. At present about 11,000 B.T.U. (British the mal heat units) are expended to produce one kilowatt-hour of electricity A pound of coal may yield upon combustion from 6000 to 15,000 B.T.U We are therefore getting little better than one kilowatt-hour per pound coal. This could be considerably increased. Second, we need a lighte faster, and more efficient prime power-producer than our present steam an Diesel engines. Finally, we need a method of storing electrical energy i order that our generating capacity may be fully used at all times, with th extra current being supplied at peak load from the stored energy.

SUMMARY

1. The unit of electric power is the watt. Watts = volts × amperes. Vario household appliances usually have wattage stipulated.
2. We buy electric energy or kilowatt-hours.

$$\text{Kilowatt-hours} = \frac{\text{watts} \times \text{hours}}{1000}$$

3. Work must be done to produce electricity. Other forms of energy mus

therefore, be transformed to electrical energy. Primary energy sources used are wind, coal, oil, and water power.

The distribution of electric power in a city and across country is accomplished by long-distance transmission at high voltages, substations, and an interlocking network.

The use of water power for the generation of electricity is being extensively developed in this country. Water power is cheaper, but the sources are often remote from the great centers of population.

Trains, ships, automobiles, and airplanes all carry their power plants. Ships and trains may be electrically driven. Diesel power is used for the generation of electricity, which in turn operates motors connected to the propellers or driving axle.

Nuclear energy may be available for the peace-time production of energy in a comparatively short time. However, an improvement in the efficiency of some of the machines now used for the conversion of energy is desirable.

STUDY EXERCISES

Show by a single mathematical equation that the watt is a unit of power but that the kilowatt-hour is a unit of work or energy.

(*a*) Calculate the current which a 75-watt lamp draws on a 110-volt circuit. (*b*) What is the resistance of the lamp?

In a home there are the following devices operated by 110-volt 60-cycle A.C. current: a one-fourth H.P. motor running 150 hours per month; six 40-watt lamps burning, on the average, 60 hours per month; four 75-watt lamps burning 80 hours per month. Calculate the monthly bill at three cents per kilowatt-hour.

What is the energy consumption per month (thirty days) of a 1.8-watt electric clock? What is the cost of operation per year at three cents per kilowatt-hour?

Make a list of energy sources other than fuels which might be used to operate an electric generator. Of these which one is most used at present? Give reasons.

List all the reasons you can find for the adoption of locomotive electric power plants — that is, the Diesel electric system used by the railroads — in preference to the central power plant which feeds electricity to the train by an overhead trolley.

Why are the Diesel-powered trains run by electricity rather than by direct use of the Diesel power as are trucks and some boats? How is the speed of the Diesel electric locomotive controlled?

In a text published in 1884 is shown a drawing of an electrified farm — that is, a threshing scene at night illuminated by electric arc lights. Why has the adoption of electricity in rural sections been so slow?

The water-power-operated generator rotates at a much slower rate than the steam-powered generator, yet is capable of developing very high electric power. How is this possible?

10. Briefly discuss each of the following subjects:
   (*a*) Although coal is, in general, our cheapest power source, its use is bot inefficient and temporary.
   (*b*) The wise and proper use of nuclear energy is one of the greatest challeng ever faced by man.
   (*c*) At present we are just in the initial stages of a great expansion in the u of electricity, yet it is more than one hundred years since Faraday disco ered electromagnetic induction.
   (*d*) The Grand Coulee power plant when complete would be capable of ligh ing New York, Chicago, Philadelphia, and other large cities, but it w not be used for that purpose.
   (*e*) Will there possibly be a shift of population centers to the vicinity water-power sources as the coal and petroleum supply is depleted?
   (*f*) The strategic advantages and disadvantages of great power centers.
11. The chemical cell is a much more efficient machine for the production of t electric current than the wasteful series of energy transformations from t chemical energy of coal to steam, to mechanical energy, to electrical energ Why, then, is the primary cell not more used? Recalling the molecular a atomic structure of carbon, state why coal cannot be used as the negati plate of a primary cell.

FOR FURTHER READING

1. Bragg, W. L., *Electricity.*
   Chapter IV makes alternating current, electrical units, and the intricacies power generation and distribution quite clear. Excellent.
2. Stephenson, R. J., *Exploring in Physics.*
   In Chapter 10 the author reviews electricity with special attention to the vario electrical units and Ohm's law.
3. Lovell, Alfred H., *Generating Stations.* New York: McGraw-Hill Bo Company, Inc., 1941.
   While this book is primarily for the electrical engineer, there is considera readable material on the economic aspects of power generation, its cost, the ty of equipment in large municipal and federal power plants, their output, a systems of distribution.

40

Transmitting Energy by Wave Motion

E HAVE LEARNED of the significance of energy and the machines that ilize energy to carry on the many activities of this technical age. We ıve had much to say concerning certain forms of energy — potential and netic energy, electrical energy, chemical energy, heat energy — but have udiously avoided many other forms of energy, such as X-rays, cosmic ys, sound, ultra-violet rays, and infra-red rays. These forms of energy e far from being unimportant, but are very different from the forms of ergy studied thus far. Many persons daily use their radios without giv-g a thought to the many energy transformations involved in its opera-on. Electrical energy is used to operate the broadcasting station. hough much of the energy sent into the station is wasted in heating the any circuits that are a part of every sending station, there is a large frac-on which cannot be thus accounted for and which is said to be *radiated* by e station. It streams out into space with the velocity of light — 186,000 iles per second — in all directions. Only a minute fraction of this energy intercepted by a radio set in the form of a radio program. The send-g station transmits energy, but how? The easy answer is to say "radio ıves," but, of course, such an answer is not an explanation.

Consider another example of energy transmission by a process which is ssociated from matter — the light from the sun. The scientist speaks arnedly of visible light and also of invisible light, such as the infra-red ıd the ultra-violet radiation from the sun. We know this visible and visible light comes to us from the sun in a time interval of about eight inutes. We also know that many things are done through the agency of ;ht: plants need it for growth; it provides bodily warmth; it causes the asons; it is responsible for our weather; we can take photographs with it. aturally, all these transformations require energy, and we realize that the ergy for all these changes came from the sun through ninety-three million iles of practically empty space. It is not a mere academic question to k, What is light? To reply that light is a form of wave motion is not an tirely obvious answer. In this chapter the principal aim will be to lay a m foundation for an understanding of wave motion as an important ethod of transmitting energy.

Wave Motion

A visible and common example of wave motion is that of water wav Nearly everyone has watched an empty can or bottle bobbing up and do on the waves near the shore of a lake. The waves keep rolling up on t beach for hours, but somehow the water itself does not pile up on the bea to any considerable extent. If the floating object is quite heavy, there will very little or no motion of it toward the shore, while hundreds of waves pa by, causing it to bob up and down. The floating object thus serves to in cate that the water is not moving forward with the waves. It is appare then, that a water wave is a *shape* and a *regular sequence of motion* th moves toward the shore and carries energy with it.

Other examples of water waves, such as those generated when a swimm dives into a body of water, are often observed. Water waves are always t result of (1) an initial disturbance in the water, which requires an expen ture of energy, and of (2) a certain *regular oscillatory* (up-and-down) *moti* of the water itself. A familiar example of regular oscillatory motion is th of a common pendulum bob, in which there is a continuous transformati of potential into kinetic energy and vice versa. (Refer to Figure 36 When the bob is in position P_1, the energy is entirely potential; when it fa to position P_0, the energy is entirely kinetic; it is again entirely potent when it reaches position P_2. The regularity of this to-and-fro motion fin application in the common pendulum clock. Since there is very little l of energy during the time of any one swing, a pendulum once set in moti oscillates for a long time. The behavior of any given pendulum is c scribed in terms of its *frequency*, *period*, and *amplitude*. The maximu distance the bob is displaced from its point of rest is called its *amplitude* distance a in Figure 367. The period is the length of time — usually seconds — required for one vibration; from position P_1 to P_2 and back P_1. This is often difficult to measure rectly. However, it can be readily calculat from the *frequency*, which is simply t number of complete vibrations per seco It should be apparent that as the peri gets shorter, the frequency must get great or

$$f(\text{requency}) = \frac{1}{p(\text{eriod})} = \frac{1}{t(\text{ime})}.$$

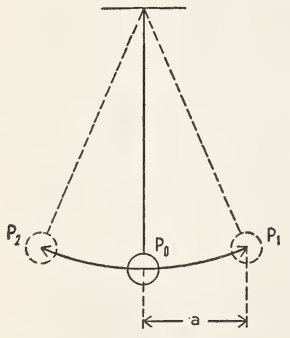


FIGURE 367. ESSENTIALS OF VIBRATORY MOTION

A somewhat less familiar example of periodic (oscillatory) motion is that of mass bobbing up and down on a spring. the mass m in Figure 368 is pulled down fr position P_0 to P_1 and released, it will oscill up and down with a definite frequency a

eriod. Changing the amplitude does not change ıe frequency. This is also true of the pendulum ı Figure 367 and is an important characteristic of scillating systems in general. If the mass is dis-laced to a greater distance P_1', a greater restoring rce f_1' will be required — a conclusion based upon ewton's Third Law of Motion. Experiment proves ıat the enhanced restoring force at P_1' will give ıough greater acceleration to m to make the time ecessary to travel back to the point of rest the me as when it originally started from P_1. When ıe mass reaches the original point of rest, P_0, its ertia then carries it up to compress the spring. ence it gradually slows down until its motion is gain zero, position P'_2. The forces of compression ıen send it traveling downward again, and this cle is repeated many times.

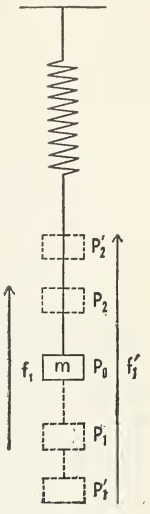


FIGURE 368
VIBRATORY MOTION
IN A SPRING

It is easy to show that the frequency of vibration the mass m can be increased by increasing the iffness (restoring force, or elasticity) of the spring by decreasing the mass of m. The scientist sum-arizes these facts in the statement that the fre-ıency of an oscillating system increases with an in-ease in the restoring force (elasticity) and decreases with an increase mass, or

$$f(\text{requency}) \propto \frac{e(\text{lasticity})}{m(\text{ass})}$$

Now let us return to the subject of the propagation and transmission of ıter waves. Suppose a mass m is made to oscillate up and down on a itable spring (Figure 369) in such a way as just to touch the surface of the ıter. Water waves, of course, travel out in all directions with a measur-ble forward velocity, as the water surface oscillates only with an up-and-own motion.[1] These waves will pass by the point A with a definite fre-

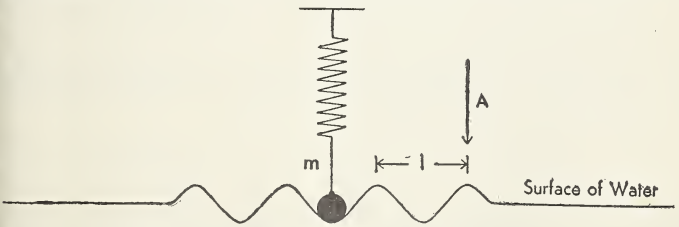


FIGURE 369. PRODUCTION OF WATER WAVES

[1] This discussion is concerned only with the visible surface wave, not with the movement of ter beneath the surface.

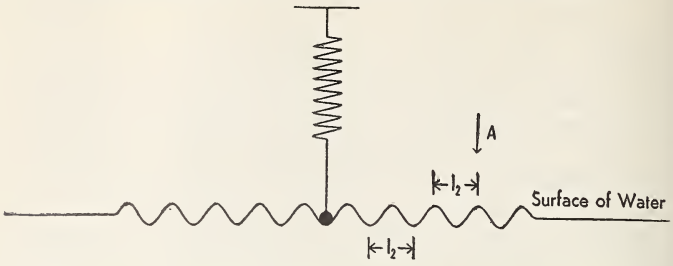


FIGURE 370. WATER WAVES OF DIFFERENT FREQUENCIES

quency. If the mass m is made smaller so that the frequency of oscillatio is increased, it is found that the number of waves passing the point A pe second (the frequency) is also increased (Figure 370). This shows tha there is a relationship between the number, or frequency, of disturbanc of the weight and the number of waves that pass point A per second (whic is the frequency). Many experiments have also proved that the time fo the wave-front to travel from the seat of disturbance to A is substantiall the same.[1] In other words, the velocity of propagation of the disturban through the water is determined by the water itself. Notice also that th distance from crest to crest, or from trough to trough, called the wav length, l, *decreases* as the frequency *increases*.

We have discussed two characteristics of two separate trains of waves - their frequency and their velocity. The two waves differ in another impo tant characteristic — the distance from crest to crest, or the distance fro trough to trough, which is referred to as the wave length. A little reflectio will convince you that these three characteristics of water waves — th frequency (f), the wave length (l), and the velocity (v) — must be relate as follows:

$$v(\text{elocity}) = f(\text{requency}) \times l(\text{ength}).$$

An observer at A in Figure 371 starts counting 0, 1, 2, 3, and so on, as wav crests pass him, until he finds that f waves go by each second. If the di tance from crest to crest is l, the wave length, it should be obvious that

[1] Strictly speaking this statement is true only for water waves that are very long in compa ison with the depth of the wave and for certain short waves (ripples) whose wave length is of t order of one centimeter. The following data are illustrative of the relationships between f quency (f), wave length (l), and velocity (v) in the latter range:

f	l	v
15 v.p.s.	1.55 cm	23.2 cm/sec
20 "	1.19 "	23.8 "
25 "	0.99 "	24.8 "

The reader is warned that this has not been a complete discussion of all the factors involved the velocity of water waves. The important point for our purpose is that the *frequency* increas as the wave length *decreases*.

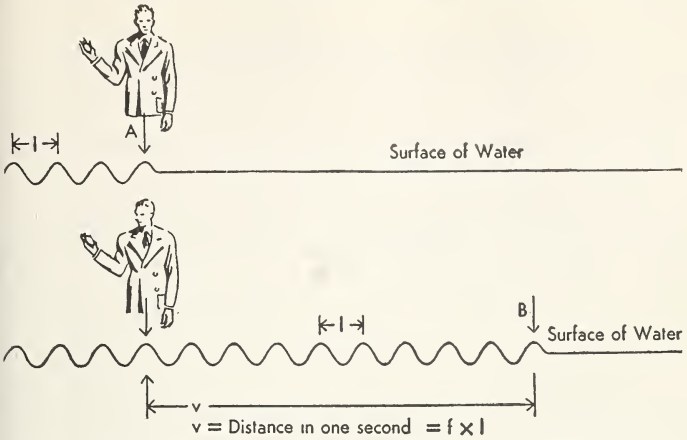


FIGURE 371. THE RELATION BETWEEN VELOCITY, FREQUENCY, AND THE WAVE-LENGTH

ıe end of the first second the first wave front would be at *B*, a distance 'hich is equal to $f \times l$. In other words, v = distance covered in one second y a particular wave front = fl. This equation has been found to describe ıe velocity of any form of wave motion. It is one of the two fundamental quations pertaining to wave motion.

The actual velocity of a wave, however, is dependent upon the medium ı which it is being propagated. If, for example, another liquid, such as lcohol, is used in place of water in Figures 369 and 370, it is found that the 'equency of the waves remains the same — this is dependent upon the fre- uency of the spring — but that the velocity is less, and the wave length also less. The answer to this puzzle is found on page 729, where the fre- uency of the oscillating spring was found to be dependent upon the restor- ıg force and the inertia. The water layer when disturbed has a tendency) return to its original smooth surface because of its restoring force. The :storing force here is due to the combined effect of *g*, the acceleration due) gravity, and the force of surface tension. In effect, the surface of the ater acts in a manner analogous to the rubber membrane of a large toy alloon. An indentation made by a finger remains only as long as the nger is held in place. This membrane effect existing in the surface of a quid is referred to as *surface tension*. The force of surface tension is oper- ting everywhere in the rippled water surface, tending to eliminate both ıe crests and troughs by shortening the water surface. At the same time ıe water in the crests has been lifted above its original rest position gainst the pull of gravity. Thus, there is a second restoring force due to

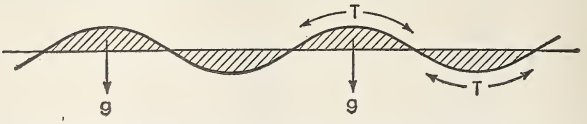


FIGURE 372. FORCES INVOLVED IN PRODUCTION OF RIPPLES — SURFACE TENSION AND GRAVITY

gravity g. (Refer to Figure 372.) These two combined effects then constitute a restoring force which causes the water to return to its original position. However, the inertia of the water carries it above and below the position of rest, and thus the water is set into an oscillatory motion which sends forth a train of waves with a frequency which is the same as that of the disturbing oscillating spring, and with a characteristic velocity. When alcohol is substituted for water, the restoring force existing in the distorted surface of the alcohol when disturbed by the oscillating weight is less; hence there is less tendency for the alcohol surface to return to its original condition, which is manifested in a lower wave velocity even though the frequency of the alcohol waves is the same as that of the water waves. In other words, the velocity of a series of waves is directly proportional to the wave length if the frequency remains unchanged.

The scientist summarizes all the above information concerning waves in a very compact mathematical relation which we owe to Sir Isaac Newton, namely:

$$v(\text{elocity}) \propto \sqrt{\frac{\text{Restoring force}}{\text{Inertia per unit volume}}}$$

Restoring force is the general term used to refer to the tendency of any substance to return to its original shape or condition after being distorted by some outside force. The restoring force and the density vary from liquid to liquid, and the two combine to determine the velocity of oscillatory surface waves in liquids. To summarize, then, it may be said that the velocity of any particular form of wave motion is determined by the characteristics of the medium.

The foregoing experiments indicate that there are three properties essential to wave transmission along the surface of a liquid:

(1) There must be a tendency for the medium to return to its original condition after being disturbed — a property known as elasticity or restoring force.

(2) The medium must have inertia in order to store up energy of motion.

(3) The frictional resistance within the medium must not be great enough to prevent oscillatory motion.

So far our discussion has been limited entirely to the visible ripples that travel over liquid surfaces. The propagation of large water waves can be described in a manner entirely analogous to those of ripples. The two

inds of waves differ only in the nature of the restoring force which causes ıe medium to oscillate. For large waves, the restoring force is largely that ue to the effect of gravity on the displaced water. We are going to find ıat in nature regular vibratory motions of various kinds are very common. ɔme examples of this kind of motion are easy to perceive and understand. ut to insist that energy is transmitted from the sun to the earth, a distance ninety-three million miles, in eight minutes and also by a *transverse* vibra- ɔry wave motion is apt to be perplexing. There must be certain criteria ıat can be applied to establish the fact that light waves have character- tics entirely similar to those of the water waves that we have been udying.

ıe Attributes of Wave Motion

The principal attributes connected with the motion of waves of every escription are as follows:

1. *Waves can be reflected.* If on a quiet day pebbles are thrown into the ater, ripples will move out rapidly in ever-increasing concentric circles. hen the circular waves strike a floating board, they are reflected in such way as to preserve their circular form and they travel back right through e oncoming waves. (Refer to Figure 373.)

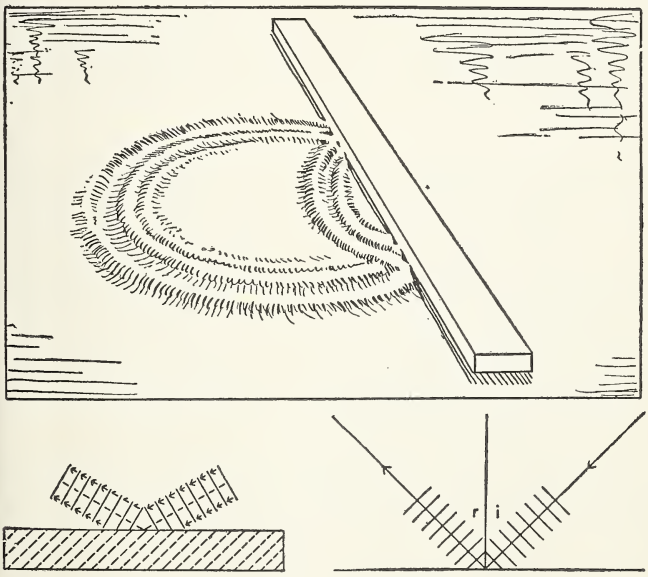


FIGURE 373. REFLECTION OF WATER WAVES

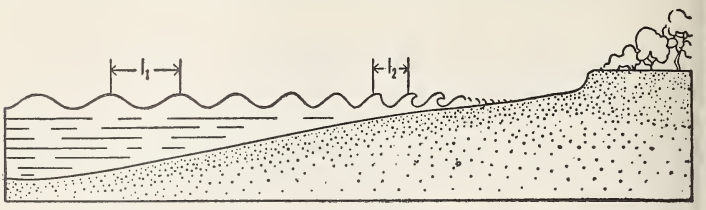


FIGURE 374. REFRACTION OF WATER WAVES

If a train of straight waves is allowed to strike a flat surface at an angl it is found that the reflected waves make the same angle with a perpe dicular to the reflecting surface as the incident waves; that is, the angle *r*(eflection) is equal to the angle of *i*(ncidence). This generalization called the *Law of Reflection.* (Refer to Figure 373.)

2. *Waves can be refracted. Refraction* is the term used to refer to a chang in the direction due to a change in the velocity of a wave because of son change in the characteristics of the propagating medium. Large wat waves undergo refraction as they approach a gently sloping beach. Thu in Figure 374, the distance from crest to crest where the water is deep constant. But as the wave gets into shallower water, the beach itse offers frictional resistance to the oscillatory motion of the water, which r duces the wave length, though there is little or no change in the frequenc The forward velocity of the waves, then, is reduced because of the decrea in wave length.

If waves approach a beach at an angle, refraction manifests itself in change in direction as well as in a change in velocity. The change direction, in this case, is a consequence of the change in velocity, and th effect is also called refraction. (Refer to Figure 375.) As the shorewar end of a wave approaches shallow water, its forward velocity is reduce However, the portion of the wave out in deep water is still traveling with i original velocity and is rushing shoreward faster than the retarded en This results in a definite change in the direction of travel of the waves. the language of the scientist, the waves are refracted. It should be note that in refraction there are usually two concomitant effects: a change in th velocity of the wave and a change in its direction of travel.

3. *Waves from different sources can reinforce each other.* In Figure 376 a shown two masses, *A* and *B*, suspended on springs which oscillate with di ferent periods. They can be used to start a series of waves of different fr quencies through the water. If *A* is set oscillating alone, a train of wav of frequency f_1 and wave length l_1 is sent out in all directions through th water. If *B* is made to oscillate alone, a wave train of different frequen f_2 and wave length l_2 is set in motion. Now, what sort of wave motio

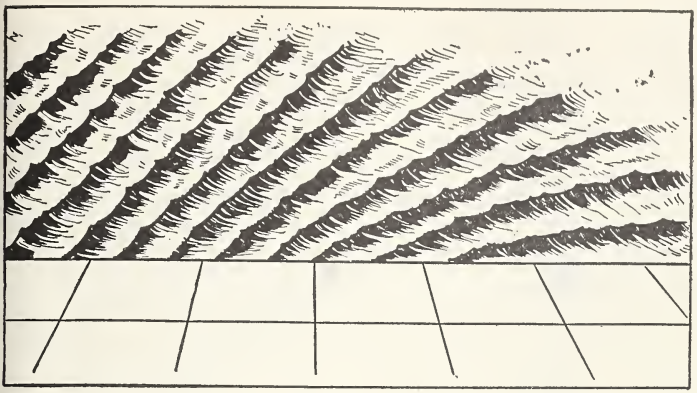


FIGURE 375
REFRACTION MEANS CHANGE IN VELOCITY AND DIRECTION OF WAVES

ould result if *A* and *B* were made to oscillate simultaneously? Of course, ıe faster one, say *A*, will at various times be out of step with *B*, and at ther times it will be exactly in step. When *A* is going down past its point f rest on its downward travel just as *B* is doing the same thing, the two ıasses may be said to be exactly "in step." If *B* were moving upward at ıat same instant, then *A* and *B* would be completely "out of step" with ıch other.

Referring to Figure 376, what kind of wave motion does result when *A* ıd *B* oscillate simultaneously? A moment's reflection will show that the ngle wave that results must represent some sort of fusion of the two aves. There will be moments when the displacement (amplitude) of one ave will be added to that of the second wave. This is called *constructive terference.* Likewise there will be moments when different portions of ıe two waves will be out of step with each other; then there will be a re-ıced displacement of the medium, water. This is referred to as *destructive terference.* In other words, there will be moments when the displacement the medium due to one wave will be additive with respect to the corre-ponding displacement of the second wave, and vice versa. The resulting ave form is shown in Figure 376. The phenomenon of interference is one the very important characteristics of wave motion. Later we shall see ıat the test of reinforcement can be used to prove whether or not a peri-lic motion is a form of wave motion.

4. *Waves from different sources can interfere with each other.* It is obvious ɔm the discussion in the preceding section that there will be moments hen the parts of different waves will be wholly out of phase with each

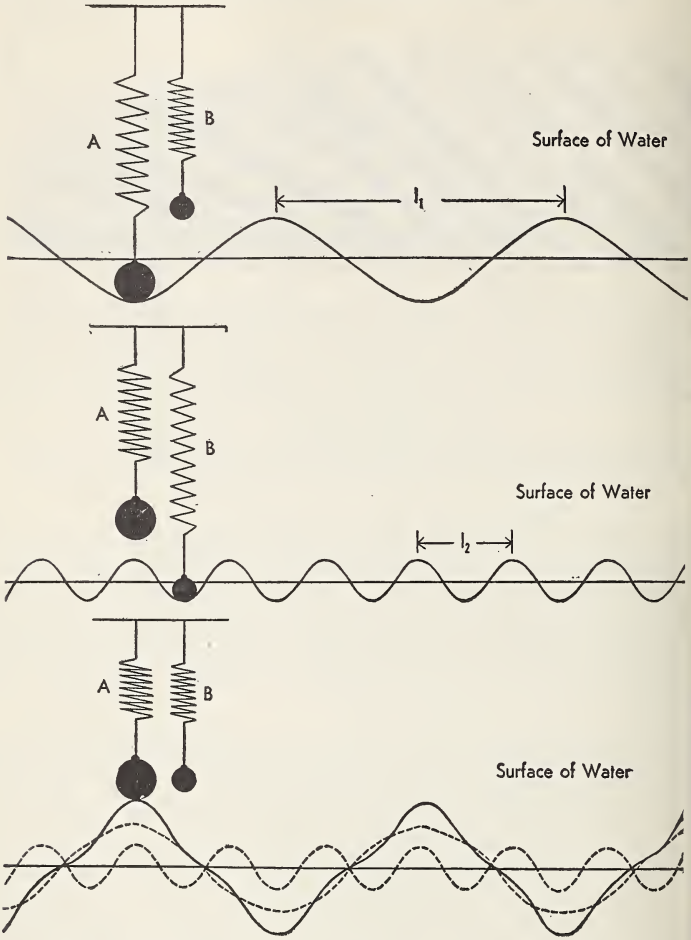


FIGURE 376. DIFFERENT WAVE TRAINS CAN INTERFERE OR REINFORCE EACH OTHER

other. Then one wave completely interferes with the other, and no motion of the medium results. There is thus complete interference. Soldiers are always ordered to break step when marching across a bridge. There must be some up-and-down motion of the bridge as troops march across. Theoretically, if the soldiers "broke step" and it was possible to get the stepping motion of every soldier completely "out of step" with that of some other

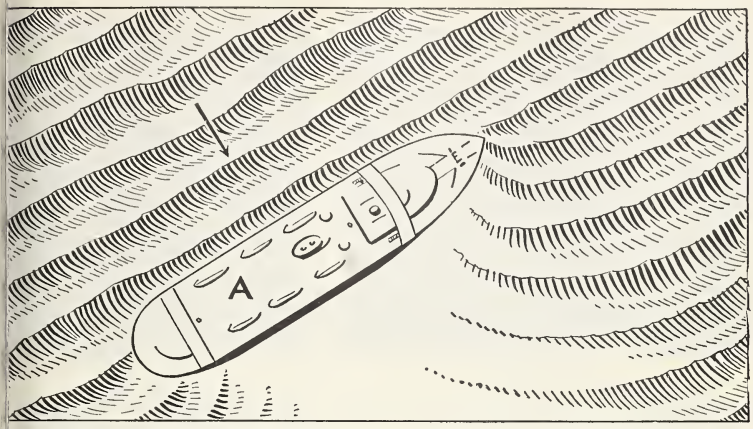


FIGURE 377. DIFFRACTION OF WATER WAVES — HUYGENS' PRINCIPLE

oldier, the entire bridge would remain relatively stationary. Actually, of ourse, it would be impossible to achieve such a result, but enough of an pproximation to this state of affairs can be reached by having the soldiers "break step" in a random fashion, so that it is then safe to march across he bridge. Later we are going to find that in nature we shall meet with ther examples of constructive interference and destructive interference.

5. *Waves can be diffracted.* The bending of waves around corners or harp edges is called diffraction. The energy of a wave must be carried rom particle to particle in the medium. Each particle in a wave front can e regarded as an independent source of disturbance for setting other par- icles in oscillation. This is known as Huygens' principle, after a Dutch cientist who was among the first to advocate the theory of the transmission f light by waves. It is Huygens' principle that accounts for the ever- idening circular waves formed when a pebble is dropped into the water.

Huygens' principle can be used to account for the bending of water vaves around a sharp edge. (Refer to Figure 377.) When disturbed, the vater particles right at the ship's prow affect all other particles in their icinity, and thus generate a wave front more or less circular in form, which noves into the quiet water beside the vessel.

Two striking illustrations of Huygens' principle are shown in Figures 378 nd 379. In Figure 378, a ripple striking an aperture acts as an independ- nt source of disturbance to set up a new series of circular waves. In igure 379, two sets of circular waves created at two apertures travel hrough each other, resulting in constructive and destructive interference ffects.

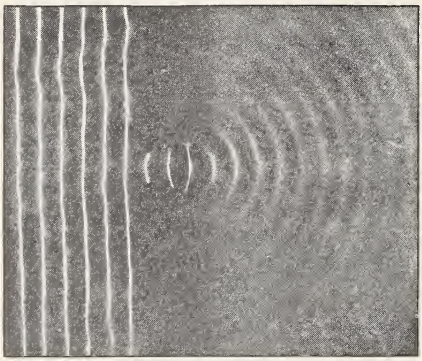


FIGURE 378
DIFFRACTION OF A RIPPLE UPON PASSING THROUGH AN APERTURE

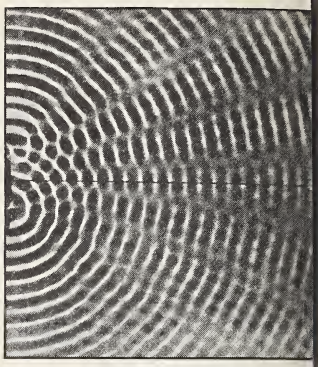


FIGURE 379
INTERFERENCE PATTERN BETWEEN TWO TRAINS OF RIPPLE

(From "General Physics for Colleges," by Webster, Farwell, and Drew. The Century Company, publishers)

6. *The Doppler effect is characteristic of wave motions.* This effect will b utilized later to establish the fact that sound and light also are examples o wave motion. So far our discussion of water waves has been limited t situations in which the source or cause of the waves and also the mediu are stationary with respect to each other. However, if either the source o the waves, the medium, or the position of the observer change with respe to each other, there must be a change in the frequency and the wave lengt as a result of this motion. (Refer to Figure 380.) If the fisherman caus his bob to move up and down in a regular manner, a series of water wav of definite frequency and wave length will move out in ever-widening circl from the seat of disturbance. As indicated before, the velocity of this wav will be determined by the characteristics of the liquid. The frequency wi be determined by the frequency of the bob, and the wave-length will depen upon the function:

$$l = \frac{v}{f}, \text{ since } v = fl.$$

Suppose, however, that the fisherman walks forward along the shore whil the bob is oscillating up and down. (Refer to Figure 380, *b*.) Then the wav length of the waves in front of the bob will be *less* than in Figure 380 (*a*) while the wave length of the waves behind the bob will be considerabl longer. The explanation is as follows. As shown before, the length o the water wave when the bob is stationary is expressed:

$$l = \frac{v}{f}$$

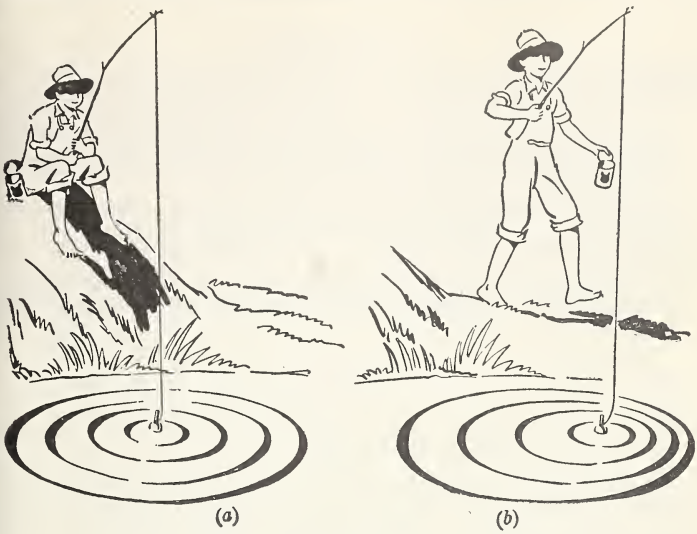


FIGURE 380

(*a*) *Production of a train of waves by a stationary source;* (*b*) *production of a train of waves by a moving source — Doppler's principle*

However, if the oscillating bob moves forward during the course of a complete oscillation, the next disturbance of the water will result in a shorter wave l_2 by the amount that the bob has moved forward. For the same reason the wave length of the waves behind the bob must be greater. Yet the velocity of the wave is constant, which means that the frequency must be greater for the waves in front of the bob, and smaller for the waves behind it.

This phenomenon is known as the *Doppler effect*, after the man who first clearly stated the principle: *the apparent frequency of waves will be increased and the wave length decreased if the cause of the waves moves toward the observer, or if the observer moves toward the wave source, and vice versa.* The following experiment further illustrates this principle. A person in an anchored boat can determine the frequency of the waves passing the boat by simply counting the number of wave crests that pass each second. These waves, of course, will have a definite wave length. Obviously, the number of wave crests that the rower will count per second will be greater if the boat is also moving toward the source of the waves and the wave length would apparently decrease.

SUMMARY

1. Energy can be transferred through water with water waves.
2. Water waves are the result of a disturbance (expenditure of energy) in water surface which causes an oscillatory up-and-down motion of the wate which propagates the wave motion. The water remains stationary wit respect to the forward motion of the wave.
3. In any regular vibratory motion the time in seconds for one complete vibra tion, down and up ($\downarrow\uparrow$) or to and fro ($\rightleftarrows$), is called the period.
4. In any regular vibratory motion, the number of complete vibrations per sec ond is called the frequency. The frequency and the period are related a follows:

$$f \propto \frac{1}{p} \propto \frac{1}{t}$$

5. The maximum displacement of a medium or body in vibratory motion fro its rest position is called its amplitude.
6. The frequency of an oscillating system is directly proportional to the elastic ity of the substance (restoring force) and inversely proportional to the mas of the oscillating system. The exact nature of the restoring force depend upon the nature of the oscillating system.
7. The wave length of a water wave is the distance from a crest or trough to th next crest or trough. The restoring force of water is due to the combine effects of the gravitational pull on the displaced water and the force o surface tension.
8. The velocity of a wave is the distance that a given wave front will travel i unit time. The velocity is related to the frequency and wave length as fol lows: $v = f \times l.$
9. The following characteristics are often used to identify a wave motion:
   (*a*) Waves can be reflected.
   (*b*) Waves can be refracted.
   (*c*) Waves from different sources can reinforce or interfere with each other that is, undergo constructive and destructive interference.
   (*d*) Waves can be diffracted.
   (*e*) Waves undergo the Doppler effect.
10. Refraction refers to a change in the direction of travel of a wave due to a change in its velocity.
11. The bending of a wave around corners or sharp edges is called diffraction.
12. A change in the wave length and frequency of a series of waves as a result o the source of the waves approaching or receding from the observer, or vic versa, is known as the Doppler effect.
13. Waves in which the movement of the medium is essentially perpendicular t the direction of travel are called transverse waves.

STUDY EXERCISES

1. Associate by number the terms given at the right with the various statements recorded below:

.... The distance that a medium is displaced from its rest position, while transferring a wave motion.
.... The property of a substance which causes it to return to its original condition after being distorted by force.
.... The time required for one complete vibration of a substance or body in a regular oscillatory motion.
.... The length from crest to crest or from trough to trough in a series of water waves.
.... The change in the direction of travel of water waves as they approach shore as a result of an actual decrease in the velocity of the water waves.

1. Reflection
2. Refraction
3. Diffraction
4. Resonance
5. Interference
6. Reinforcement
7. Amplitude
8. Frequency
9. Period
10. Elasticity
11. Wave length
12. Doppler effect

.... The number of complete vibrations per second in any body or medium undergoing a regular oscillatory motion.
.... A rower rows directly into the wind. The number of wave crests that pass him each second is greater than when his boat is anchored. What does this illustrate?
.... A change in the direction of travel of a wave motion in which the angle of incidence is equal to the angle of reflection. This illustrates what phenomenon?
.... The bending of waves round the corner of an obstacle.
.... A reduced displacement of the medium as a result of the union of two or more sets of waves of different wave lengths.
.... An enhanced displacement of a medium as a result of the union of two or more sets of waves of different wave lengths.
.... Properly timed pushes of a child in a swing soon cause a noticeable to-and-fro motion.

2. Shallow water waves travel about 125 cm per second.
   (*a*) If a stone is dropped into a quiet pond of water, how far will the first wave travel in fifteen seconds?
   (*b*) If the wave length is 100 cm, what is the frequency? The period?
3. A stone was dropped into a quiet pool of water. The first wave was observed to travel 100 feet in 25 seconds.
   (*a*) What is the velocity of the wave?
   (*b*) Experimentally the number of wave crests passing a given point was found to be seventy-five per minute. What is the frequency of the water waves? What is the wave length in feet?

FOR FURTHER READING

1. Lemon, H. B., *From Galileo to the Nuclear Age.*

The meaning of wave motion, and the phenomena associated with waves – reflection, refraction, diffraction, constructive and destructive interference, an the Doppler effect — are very interestingly presented in Chapters 35 and 36.

2. Stephenson, R. J., *Exploring in Physics.*

An excellent way to find out how well one understands the fundamentals c wave motion is to solve actual problems illustrating those fundamentals. Ther are a number of simple but practicable problems of this type in Chapter 12.

3. Eyring, C. F., *Survey Course in Physics.*

The characteristics of various vibrating systems are discussed in Chapter VII The fundamentals of wave motion are clearly stated in pages 158–170 of Chapte IX. The discussion is complete and in non-technical language.

41

The Nature of Sound

AN EXCELLENT ILLUSTRATION of the great difference between subjective information and objective information is found in answers to the question, "What is sound?" It is easy to start interminable arguments in any discussion group by raising the question, "If a tree falls in a distant forest with no person in the vicinity, is there any sound?" People who are concerned with the hearing mechanism and auditory sensation would answer this question in the negative. Physicists, however, who are primarily interested in the external disturbance itself, would promptly answer the question in the affirmative. The physicist knows of the imperfections of the human ear and that science has produced many devices which will hear sound that the human ear cannot hear. To the physicist, sound is a phenomenon that occurs externally to any possible observer and can therefore be described in objective terms.

It takes an expenditure of energy to produce sound, and this energy remains associated with the sound produced. It is, of course, a common experience that sound travels, which means that in discussing the subject of sound it is necessary to consider a process for transferring energy from one place to another. This should suggest to the student that sound is some kind of wave phenomenon. Modern knowledge of sound as a wave phenomenon has made possible the many methods by which we can transmit, preserve, and reproduce sound. The world of twenty years ago did not possess "high-fidelity" records, microphones, and loudspeakers. Likewise, to record sound photographically on film and then to reproduce that sound would be impossible without the modern knowledge of sound as a wave motion.

Sound as Waves

We have already seen (Chapter 40) that wave motion exhibits a number of characteristic attributes. A little reflection proves that sound possesses all these attributes, namely:

1. Sound requires an expenditure of energy for its production. Thus, striking the keys of a piano, bowing the strings of a violin, "exploding" an

inflated paper bag by suddenly crushing it between the hands, shooting firecracker, all represent an expenditure of energy and produce sound.

2. A medium is needed for the transmission of sound, and the mediu must have a tendency to return to its original condition after being dis torted. In other words, the medium for the transmission of sound must b elastic. Air, water, and such solids as concrete and steel which are highl elastic readily transmit sound. On the other hand, such materials a sponge rubber and cork have little tendency to resist changes of shape; tha is, they are relatively inelastic. It is for this reason that sponge rubber an cork serve as excellent insulators against the transmission of sound.

Sound cannot be transmitted through a vacuum. Thus, the ticking of clock placed in an evacuated chamber cannot be heard. We are foreve precluded from hearing events that occur in outer space, because most o astronomical space is devoid of matter. Our information respecting bodie in outer space can come to the earth only on beams of light, which, we late are to learn, is also a form of wave motion. Air is the usual medium for th transmission of sound, but water and many solids transmit sound with ever greater efficiency and velocity. The Indian scout of frontier days woul often detect the sound of approaching horses or marching men by listenin with his ear to the ground.

3. Sound travels with a definite velocity, which is determined by th nature of the medium. Thus, the velocity of sound in air, water, and ice all at a temperature of 0° C., is as follows:

Air:	331.4	m/sec (1087.1 ft/sec)
Water:	1450	m/sec (4750 ft/sec)
Ice:	3200	m/sec (10,500 ft/sec)

The only factor affecting the velocity of sound is the character of the me dium. Factors such as loudness, the energy associated with a wave, and th pitch (frequency) have little or no influence on velocity.

Temperature very materially affects the velocity of sound in air. Th increase in velocity amounts to about 0.6 meter, or two feet, per second fo each degree centigrade of rise in temperature. Thus, the velocity of soun in air at a temperature of 20° C. would be 1087 ft + (2 × 20) = 1127 fee per second.

4. Sound waves can be reflected. Practically everyone has encountered echoes. When sound waves strike a building, a hill, a cloud, or even a for est, they are reflected and returned to the sender — sometimes more tha once. The distance to a far-off hill can be roughly determined by timing the interval between a sound and its echo. Half the elapsed time multi plied by 1100 ft/sec gives approximately the distance in feet. This same principle can be used to determine ocean depths.

In public halls, excessive reflection from walls, floor, and ceiling lasting over an appreciable length of time interferes with hearing, an effect known

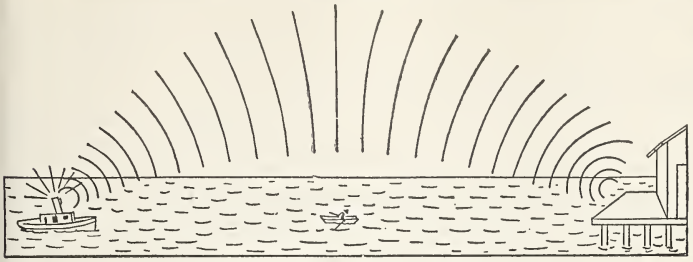


FIGURE 381. REFRACTION OF SOUND WAVES

reverberation. A method frequently used to overcome excessive reverberation is that of using sound-absorbing surfaces, such as heavy drapes and acoustic tiles, which function by absorbing the sound as it strikes these surfaces and thus prevent excessive reflection.

5. Under certain conditions the direction of travel of sound changes — the phenomenon known as *refraction.* The characteristics of air as a medium for transmitting sound change with temperature, sound traveling faster in warm air. Many persons have observed that sound seems to travel "farther" at night than in the daytime. The true explanation of this is that the sound path is bent. In Figure 381 the air near the water surface is much cooler than the air above. Hence the upper end of the wave front travels faster, and in this way the wave front returns to the surface of the earth again. Thus it happens that a person on a wharf can distinctly hear the boat whistle out on the water, while another person in a boat in an intermediate position may not hear the sound.

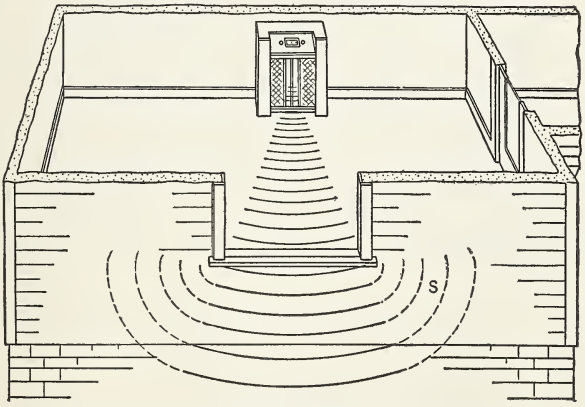


FIGURE 382. DIFFRACTION OF SOUND WAVES

In the daytime the conditions shown in Figure 381 would be reversed, i that the air near the surface of the water would be warmer than the a above. Hence the sound path would be bent *away* from the surface of th water and continually move away from it.

6. The direction of travel of sound is also changed by sharp edges o small openings. It is this phenomenon that accounts for the fact tha sound can "bend around corners." Sound shadows exist, but they are no nearly so definite as in the case of light shadows, because of the relativel great diffraction effects of sound. Thus, in Figure 382 the sound from th radio is absorbed or reflected when it strikes the opposite wall. Only th sound that strikes the open window passes to the outside. The region indicated by *s* would be in a full sound shadow if the sound traveled only i straight lines. However, some of the sound is diffracted at the edges of th window.

7. Under certain conditions, union of sound effects results in a decrease i sound or in amplification. The phenomena of constructive and destructiv interference is as common in connection with sound as with water waves For example, the popular percussion musical instrument, the marimba consists of a series of wooden bars of graduated lengths suspended ove tubes which are also of graduated lengths. There is a definite mathemati cal relationship between the lengths of the hollow tubes and the variou percussion bars. If middle C, for example, is struck properly, a rich ton will result. If the experiment is repeated with a plug of cotton in the uppe part of the tube the volume of the tone will be markedly reduced. Th tubes serve to amplify the tone and are called resonators. This illustrate the phenomenon of constructive interference. If the tubes for certain ton

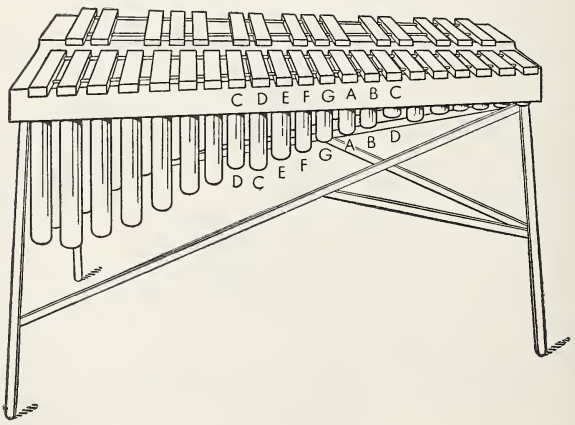


FIGURE 383
RESONANCE AND NON-RESONANCE IN A MUSICAL INSTRUMENT

ars are interchanged, as for example C and D, the effect is immediately oticeable when the bars are struck. The tone that is emitted by each tone ar is not nearly so loud, sounds harsh, and dies down in a short time. This lustrates destructive interference. The phenomenon of *beats* observed in usic illustrates destructive interference of sound waves. (Refer to page 58.)

8. The sound from a skyrocket shooting into the air decreases in *pitch.* 'wo successive notes in the musical scale differ in their pitch. The sound om the siren of an approaching fire engine is increased in pitch. The same ffect is observed if the hearer approaches the sound source. This phenomnon is referred to as the Doppler effect, discussed at the end of the preceding hapter. If the sound source moves away from the observer, or if the oberver moves away from the sound source, there is a fall in the apparent itch of the sound.

he Nature of Sound Waves

These various phenomena pertaining to sound indicate that we are here oncerned with a form of wave motion in which the movements of the meium are not obviously discernible. However, it is not difficult to show hat the medium is air actually undergoing periodic motion of a type uite different from that observed in water waves. In water waves the isible up-and-down movement of the medium is perpendicular to the irection of travel of the waves. They are therefore referred to as *transerse* waves. Sound waves, on the ther hand, are of another type called *ngitudinal* waves, in which the meium oscillates to and fro along a line *arallel* to the direction of travel of he wave. They are also referred to s *compressional* waves. A number of imple experiments serve to demontrate this to-and-fro motion. For xample, if a metal rod is clamped in he middle and rubbed lengthwise ith a cloth dusted with rosin, a clear, inging sound is produced. A ping-ong ball suspended in such a way as to rest lightly against the end of the od will swing out rapidly as the sound is produced in the rod. A "sound

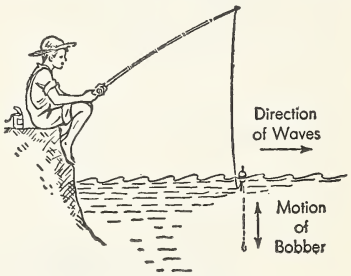


FIGURE 384
WATER WAVES ARE TRANSVERSE

FIGURE 385
SOUND WAVES ARE LONGITUDINAL OR COMPRESSIONAL WAVES

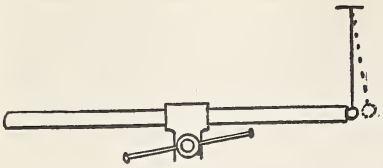


FIGURE 386. LONGITUDINAL SOUND WAVES IN A ROD

gun" can be constructed out of a closed shipping carton by cutting a round hole in the middle of one side. It is easy to snuff out a candle with a sound wave by carefully aiming the box toward the candle. By sharply hitting the back of the box, a sound wave will be produced which can be made to hit the candle flame and snuff it out even at a distance of eight to ten feet. Just before the flame is extinguished, the vertical flame will assume a horizontal position, revealing the arrival of the wave front.

The mechanism involved in the propagation of a sound wave is not difficult to understand. (Refer to Figure 388.) *A* represents a rapidly vibrating reed sending sound waves down the tube *B*. When the reed moves from position *M* to *N*, the molecules of air will be crowded closer together, forming a *condensation*. This momentary forward motion is then transmitted to the molecules in front of the united condensation, and thus it sends a disturbance (wave front) traveling down the tube. When the spring returns

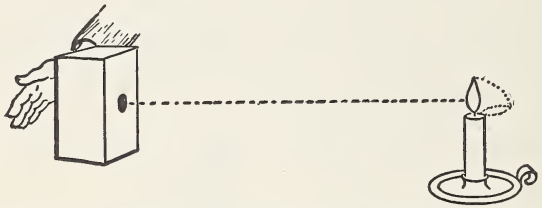


FIGURE 387. A SOUND GUN UTILIZES LONGITUDINAL WAVES

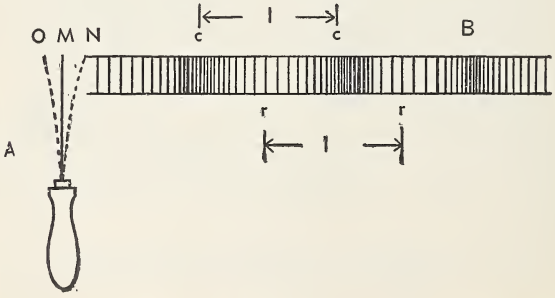


FIGURE 388
SOUND WAVES CONSIST OF CONDENSATIONS AND RAREFACTIONS

to M and continues on to O because of its inertia, it will be followed by a *rarefaction*, or partial vacuum. In this rarefaction the molecules of air will be following the reed backward. When the reed starts moving toward M and N again, there will be formed another condensation to travel down the tube. Thus, throughout the tube there will be regions of condensation and rarefaction, which constitute the mechanism for the propagation of the sound wave through air. The disturbance (wave front) progressively moves forward because of a minute vibratory motion of air particles, but no appreciable quantity of air is actually displaced from the tube. The vibratory motion of the air particles is longitudinal with respect to the motion of the wave.

The student is urged to study this mechanism carefully and to compare it with that involved in transverse waves. Note that a condensation corresponds to a crest, and a rarefaction to a trough, in transverse waves. The wave length is the distance between two successive condensations or rarefactions. The mechanism of the transmission of sound through liquids or solids is the same as through gases: that is, a transmission of energy from particle to particle in the medium with the wave front traveling forward as a condensation followed by a rarefaction. If the solid by its nature is relatively inelastic, then, as we have seen, it is incapable of transmitting sound. The actual velocity of sound in any medium is determined entirely by the properties of the medium itself, and, in general terms, it is true that sound travels faster in liquids than in gases and considerably faster in solids than in liquids, for the resistance to distortion and thus the restoring force becomes progressively larger as we pass from gases to liquids and then to solids. (Refer to page 732.)

In the experiment described in Figure 388 it is found that substituting a reed with a different rate of vibration (frequency) changes the wave length of the sound wave in accordance with the relationship $l \propto 1/f$. This must be true, since the velocity of the wave is constant for any particular substance and temperature. The relationship $v = f \times l$ holds for the velocity of sound in any medium. Actually to apply this relationship, however, requires considerable ingenuity on the part of any investigator. This can be illustrated by an experiment which has for its object the verification of the velocity of sound in air. The experiment also illustrates that sound waves are subject to interference and reinforcement phenomena. If a vibrating reed is held over a vessel partly filled with water, it is found that the volume of the sound is markedly influenced by the level of the water. (See

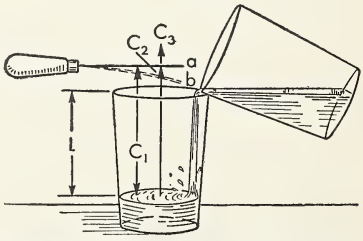


FIGURE 389. MEASURING THE VELOCITY OF SOUND IN AIR INDIRECTLY

Figure 389.) As water is poured into a tall water glass the intensity of the sound gradually increases to a maximum and then dies down as the water level rises. This illustrates the phenomenon of interference (destructive interference) and resonance (constructive interference) in a vibrating air column.

Furthermore, the length of the vibrating air column L bears a simple relationship to the wave length l, the note emitted by the fork. For example, when the reed travels from a to b, a condensation c_1 is sent traveling down the tube. This, when it strikes the surface of the water, will be reflected as a condensation c_2. If this reflected condensation returns just as the reed has finished one-half of a vibration, the reed will be starting up from position a and sending out a condensation c_3. Under these conditions c_2 will have returned just in time to reinforce the vibration of the reed and thus increase the amplitude (energy) of the new condensation c_3, which is further increased by the energy associated with the reflected condensation c_2. There is thus a marked increase in the loudness of the emitted note — a phenomenon known as resonance. Since the condensations c_1 and c_2 traveled down and up the tube during the course of one-half of a vibration, it follows that the distance $2\,L$ corresponds to one-half the wave length l,

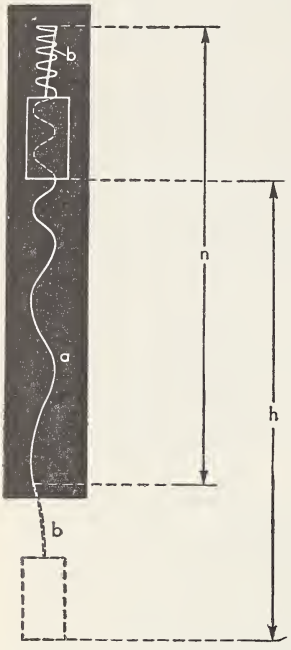


FIGURE 390. MEASURING THE FREQUENCY OF A REED

or $\frac{1}{2}\,l = 2\,L$

and $l = 4\,L.$

In other words, in a closed resonating air column the first position of resonance L corresponds to one-fourth of a wave length l.

It is still necessary to know the frequency of the vibrating reed. It is possible to attach a light stylus to the end of the vibrating reed, and to allow it to fall vertically and freely while vibrating, thus leaving a wavy trace on a piece of smoked glass. (Refer to Figure 390.) The falling fork will leave a trace which indicates the number of vibrations n made by the vibrating reed while falling a vertical distance h. The time of falling t can, of course, be calculated from the laws of falling bodies. The data obtained in such an experiment were as follows:

$L = 3.25$ inches
$h = 30$ inches, or 2.5 feet
$n = 405$

Then, wave length of sound $= l = 4\,L$
$= 4 \times 3.25 = 13$ inches $= 1.083$ feet

Time for reed to fall

$= t = \sqrt{2h/g} = \sqrt{2 \times 2.5/32} = \sqrt{2.5}/4 = 1.58/4 = 0.40$ sec.
$f = 405\ (1/.40) = 1013$
$V = 1013 \times 1.083 = 1097$ ft/sec

The Doppler effect mentioned on page 747 can readily be explained by a consideration of the nature of sound waves. The siren on a police car approaching a person will have a greater frequency (higher pitch) than if the car was stationary. For example, suppose the siren emits a tone with a frequency of five hundred vibrations per second. At a temperature of 20° C. the velocity of sound in air is about 1130 feet per second. The actual wave length of the sound waves can be calculated by the fundamental wave equation:

$$l = \frac{v}{f} = \frac{1130 \text{ ft/sec}}{500 \text{ vib/sec}} = 2.26 \text{ ft/vib}$$

This simply means that every one five-hundredths second, condensations are sent out which are separated by a distance of 2.26 feet. If the police car, however, is approaching the observer at fifty miles per hour (73.3 ft/sec), the wave length of the tone must decrease. The time that elapses between condensations is one five-hundredths second. During that interval of time, the car travels forward 73.3 ft/500 = 0.15 feet. Hence, the distance from condensation to condensation will now be 2.11 (2.26 − .15) feet. The actual new frequency to the hearer will therefore be,

$$f = v/l = \frac{1130 \text{ ft/sec}}{2.11 \text{ ft/vib}} = 536 \text{ ft/vib}$$

This means that the frequency or pitch of the siren has increased as far as the person in the street is concerned. But to the people in the moving police car the siren maintains its characteristic frequency of 500. The frequency of a sound will also increase if the hearer approaches a stationary source. If, on the other hand, either the sound source or the hearer move away from each other, the pitch of the sound will decrease.

SUMMARY

1. Observations concerning sound which indicate that some form of wave motion is involved are the following:
   (*a*) Sound requires an expenditure of energy for its production.

(*b*) A medium which resists distortion (possesses property of elasticity) is required for the propagation of sound.
(*c*) Sound travels in a given medium with a definite velocity which is determined by the characteristics of the medium — its elasticity and inertia.
(*d*) Sound waves under certain conditions undergo reflection, refraction, and diffraction.
(*e*) Sound waves can be made to interfere constructively and destructively.
(*f*) The Doppler effect takes place if the sound source changes its position with respect to a hearer.

2. Sound waves are the result of very small longitudinal to-and-fro displacements of the molecules of an elastic medium. The waves consist of alternate regions of condensation and rarefaction.
3. Sound waves will not travel through an inelastic medium or vacuum.
4. Sound travels 1087 ft/sec at 0° C. in air.
5. The velocity of sound increases 2 ft/sec per degree Centigrade increase in temperature.
6. The frequency of a series of sound waves is the same as that of the vibrating body producing the sound.
7. The fundamental equation for any wave motion, $v = f \times l$, holds for sound.
8. The wave length of a sound wave is the distance from condensation to condensation or from rarefaction to rarefaction.
9. Whenever a sound source and a hearer approach each other, the wave length of sound waves intercepted by the hearer will be decreased and the frequency (pitch) will be increased. The opposite effect will be noted when the sound source and a hearer recede from each other. This is the Doppler effect in sound.

STUDY EXERCISES

1. The following phenomena are illustrative of various attributes of sound as a wave motion. Associate by number the attribute or property of sound that best explains each phenomenon.

.... The sound of a bell on a church across a lake is inaudible during the day but is easily heard at night.
.... The windows in a house near a railroad often rattle when a whistling locomotive passes.
.... The intensity of the sound made by two airplane motors not exactly synchronized rises and falls.
.... The sound from the siren of a motorcycle policeman rises in pitch as it approaches the hearer.
.... A person's singing the pitch of middle C causes the middle C string of a near-by harp to begin sounding.
.... A person speaking in a large empty auditorium hears his voice return.
.... Sound readily penetrates into the space in the rear of the corner of a building.

1. Reflection
2. Refraction
3. Diffraction
4. Compressional wave
5. Beats
6. Interference
7. Resonance
8. Doppler effect

.... It is often impossible to play a piano and pipe organ simultaneously without producing a physiologically unpleasant effect.

.... Two sound paths carrying sound from the same source if of slightly different length result in silence.

2. The sound of the shot of a rifle was found to return from a distant hill as an echo in four seconds after the report. The temperature was 20° C. What was the distance in feet to the hill? Refer to page 744 for necessary data.

FOR FURTHER READING

1. Lemon, H. B., *From Galileo to the Nuclear Age.*
The important phenomena concerning sound are presented in Chapter 37.

2. Stephenson, R. J., *Exploring in Physics.*
The characteristics of sound waves with many problems are presented in Chapter 13.

3. Jeans, J. H., *Science and Music.* New York: The Macmillan Company, 1938.
The author is an outstanding scientist with a knack of effective writing for the non-technical reader. Sound is discussed on pages 14–36 and 105–122.

4. Eyring, C. F., *Survey Course in Physics.*
The production of sound and important facts concerning it are presented on pages 166–174. This reference presupposes that Chapters VIII and IX have been read.

42

Sound and the Individual

THUS FAR OUR DISCUSSION concerning sound has been concerned entirely with its nature in an objective sense. But we are also interested in the relation of sound to hearing. Much of our knowledge comes to us by ear; much of our enjoyment in life we owe to music, which may vary in quality from the well-blended notes of the many instruments in a symphony orchestra to the swing effect of a dance band. Music has a physiological and psychological basis as well as a physical basis. A large part of the progress that has been made during recent years in recording and reproducing sound by the radio and phonograph is the result of our knowledge concerning the science of sound. Not all sound is audible, and the sensitivity and range of audibility of the human ear vary not only between individuals but also between one's right and left ear. The average audible range is found to lie between frequencies of twenty and twenty thousand vibrations per second, though the ear is most sensitive to a frequency of about two thousand. Young people usually have a higher limit of hearing than that of old people. Sounds with frequencies greater than the audible limit are collectively referred to as *supersonics*. The sound frequencies of the human voice and of some common musical instruments are indicated in Figure 391.

What is Music?

There is a distinction between *music* and *noise*. The latter is not pleasing and consists of a jumble of many sounds of widely varying and continually changing frequencies. A pure tone in music, however, has a definite and constant frequency. A pure tone is difficult to obtain. The commonest device used to produce a definite pitch is the ordinary tuning fork. A properly constructed fork will have both its arms vibrating at the same rate, or frequency, and the tone from the vibrating fork will result from this single frequency. Because of differences in *quality* or *timbre*, the tones emitted by a violin are easily distinguished from those of a piano, even though they are of the same pitch. *Timbre*, *pitch*, and *loudness* can be used to describe the characteristics of any musical tone. *Pitch* is determined by the number of waves striking the ear per second and refers to the dominat-

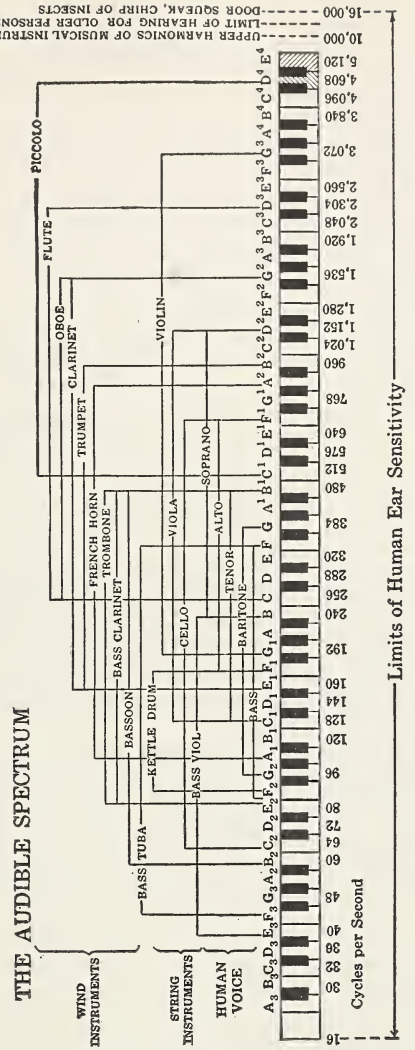


FIGURE 391. FREQUENCY RANGES OF SOME COMMON MUSICAL INSTRUMENTS

(*From "Electronics"*)

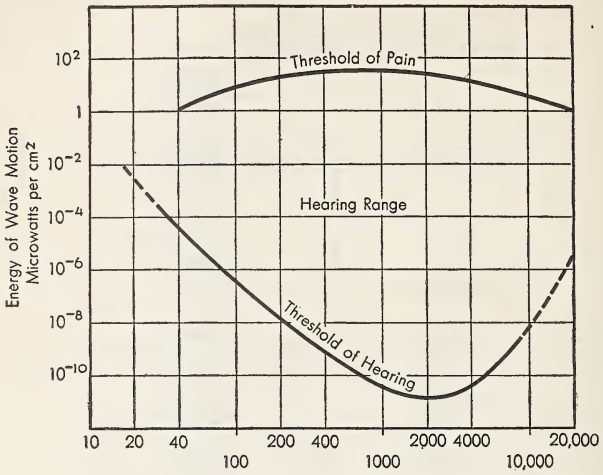


FIGURE 392
THE RELATION OF WAVE ENERGY AND FREQUENCY TO AUDIBILITY

ing frequency of the note. The pitch known to musicians as Middle C is caused by 264 waves per second striking the ear, and that of Middle G is caused by 396 vibrations per second. *Loudness* is a complex psychological reaction and is a measure of the sensation produced by sounds. It is in part due to the energy associated with the sound wave, which in turn is dependent upon the amplitude or energy of the vibrating source, and in part to the frequency of the tone.

The normal human ear is a remarkably sensitive instrument. Sound with a frequency of 2000 v.p.s. is audible if the energy of the waves exceeds 10^{-10} microwatts per square centimeter. (Refer to Figure 392.) The minuteness of this quantity of energy is brought out in the following illustration: A force of about one dyne can lift a mosquito. The energy expended in lifting the mosquito one centimeter, therefore, is

$$W = F \times d = 1 \text{ dyne} \times 1 \text{ cm} = 1 \text{ erg.}$$

Energy received at the rate of one watt corresponds to 10^7 ergs per second. Hence, energy received at the rate of 10^{-16} watts means,

$$10^{-16} \text{ watts} \times 10^7 \text{ ergs/(sec)(watt)} = 10^{-9} \text{ ergs per second.}$$

In order to accumulate enough energy at the latter rate to total one erg — enough to lift one mosquito one centimeter — it would have to be received continuously for

$$\frac{1 \text{ erg}}{10^{-9} \text{ ergs/sec}} = 10^9 \text{ sec,}$$

/hich is over thirty years. Figure 392 also indicates that sounds of fre- quency 100, and a power input of 10^{-8} microwatts per square centi- neter would be inaudible, but would be audible if the power input was 0^{-4} microwatts. Likewise, Figure 392 shows that sounds of higher fre- uencies are more easily heard than those of lower frequencies. We say hat they are *louder*. Loudness of a sound, therefore, depends upon two actors: the energy, or intensity, of the sound, and the frequency. The igh-pitched whistle of a referee at a hotly contested basketball game, for xample, can be heard above the noise of the crowd, whereas a low-pitched /histle could not be heard. That hearing depends both upon the energy f the sound waves intercepted by the ear and on their frequency is indi- ated in Figure 392. This chart indicates that the hearing mechanism eacts best to frequencies of about two thousand vibrations per second. t this frequency the energy of the sound waves may be relatively low and till be heard. In order to be heard, a sound with a frequency of forty ust have an energy content a million times as large as the minimum equired for an audible sound of two thousand frequency.

It is common knowledge that Middle C sung by a soprano, a tenor, a con- ralto, a baritone, and a bass singer will all sound differently, though they re singing the same tone. This difference, as we have seen, is attributed o different quality or timbre; and it is the different quality of the various nstruments in the modern orchestra that makes each instrument indis- ensable for the ensemble effect. Actually, the vibrations of the human oice or the various musical instruments are complex in nature, because of he union of a predominant frequency of foundation tones or *fundamentals* ith higher *harmonics* and lower *beat tones*. The harmonics, or overtones, ave frequencies of two, three, four, or other simple multiples of the foun- ation tone. For example, if a string vibrates as a whole, it will give out s fundamental frequency. But it can simultaneously vibrate in two seg- ients, and the tone then will consist of the fundamental and the first over- one or second harmonic. The tones emitted by various musical instru- ients have their characteristic quality because of the presence of many armonics in various degrees of prominence. (Refer to Figures 393 to 397.)

Thus far, the discussion has been limited to the characteristics of a single one either pure or complex because of the presence of harmonics. Music, f course, is a combination of tones that follow certain patterns of harmony. t is a part of the culture of a people. It therefore varies among different eoples and during different periods in their development. Music among rimitive peoples was based upon rhythm alone. The Indians of the South- est still carry on their ceremonial dances with no other instrument than he tom-tom to accentuate the rhythm. Advance came with the discovery hat pleasant-sounding sequences of tones could be produced with strings f various length — the lyre, or with pipes of different lengths — the pipes f Pan. This led to simple melodies played on a single instrument or sung

individually or in unison. This step in the development of modern music i illustrated by the simple nursery rhymes set to music or the sacred musi of the medieval church chanted in unison. The transition to our presen music written in many parts and adhering to certain principles of harmon came slowly as the result of experimentation. By the long process of tria and error, tonal combinations which were pleasant were adopted, and thos which were unpleasant were discarded. The names of many great musi cians — Johann Sebastian Bach, Handel, Mozart, Beethoven, Schubert Schumann, Strauss, Liszt, Wagner, Grieg, MacDowell, and others — ar associated with the development of modern occidental music. Most peopl think of music as an art to be acquired by long tedious practice and study They forget that it is also a highly developed physical science.

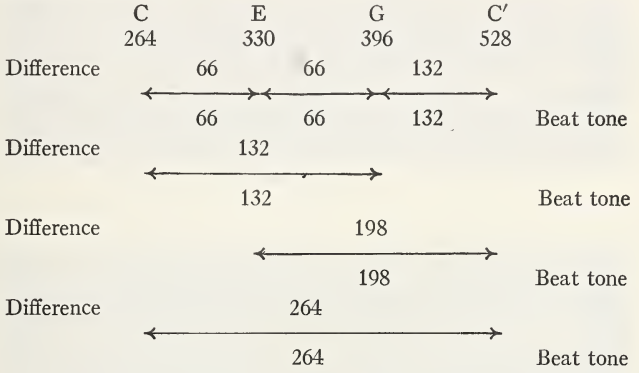
When two tones are played simultaneously we get one of three principa results:

(1) The two tones may be in unison or the frequency of one may be multiple of the other. If so, the tones blend and reinforce each other. variation of this experiment is to sing one tone only, say Middle C, close t a piano, with the sustaining pedal pressed down. It is found that Middl C or a multiple of Middle C on the piano will respond, since it has the sam frequency or a multiple thereof. A child in a swing has a natural perio of vibration. If a person times his pushes to coincide with the natura period of vibration of the swing, a series of small pushes will gradually se the child swinging through a wide arc. A series of irregular pushes woul not produce a regular to-and-fro motion. This illustrates the phenomeno of resonance and sympathetic vibration.

(2) The two tones may interfere with each other to produce unpleasan beats. They are then said to be dissonant. Imagine that two forks wit frequencies of 256 and 260 are in vibration simultaneously. The soun waves from these two forks must completely reinforce and interfere wit each other four times per second; that is, in one-eighth of a second, whil the slower fork is making 32, or 256/8, vibrations, the faster fork will mak $32\frac{1}{2}$, or 260/8 vibrations. In other words, the faster fork has gained half complete vibration and the two motions will be opposite in direction. A this point the two sound waves will destructively interfere. After anothe one-eighth of a second the slower fork will have completed 64 vibration while the faster fork will have gained another one-half vibration, and no the two waves will again be in step so as to have complete reinforcemen Thus, there will be four intervals each second of complete reinforcemen and interference of each sound — a phenomenon which is easily detecte by the average ear. The alternate swelling and decrease in volume occu ring many times per second, produces the effect commonly referred to a *beats*. The number of beats per second is equal to the difference in fr quencies of the two tones. Physiologically, beats, if few in number p second or erratic in character, have an unpleasant effect. Beats are mo

unpleasant occurring at the rate of 15 to 40 per second. Thus, C and D, and E and F, with frequency differences of 33 and $25\frac{1}{3}$, respectively, if played simultaneously, sound distinctly *discordant.*

(3) The two tones may serve to produce beat or difference tones which are pleasing to hear, since they add to the quality or timbre of the combination. When frequency of the beats is sufficiently large, the result is pleasing. For example, the notes C, E, G, and upper C on the piano have frequencies as follows:



If C and E are sounded simultaneously, there will be produced a distinct tone with a frequency of 66. That is, the diminuendo and crescendo effect due to complete reinforcement and interference 66 times per second itself produces a distinct tone. This third tone is as distinct as the two tones that produce it. It is technically called a *beat* or *difference tone.* Similarly, if C and G are played simultaneously, there will be a beat tone of 132, which is one octave below C. When E and C′ are played at the same time, a beat tone an octave below Middle G appears. Two tones which differ in frequency by a factor of two are separated by an interval of one octave. Thus, if C, E, G, and C′ are sounded simultaneously on the piano, the ear will actually hear the C's one and two octaves below Middle C, and the G tone below middle G. If C, E, G, and C′ are played with the "sustaining pedal" down, the strings one and two octaves below Middle C and the string one octave below Middle G will vibrate in sympathy.

The tonal effect of playing the four tones C, E, G, and C′ is not due entirely to the presence of beat tones. There will also be produced various harmonics of all the tones actually sounded. In Figure 393, a string is vibrating in a single segment emitting a pure tone consisting of a foundation tone. In Figures 394, 395, and 396, a string is vibrating with two, three, and four loops, causing sounds having frequencies two, three, and four times that of the foundation tone. These sounds are often referred to as the second, third, and fourth harmonics or the first, second, and third

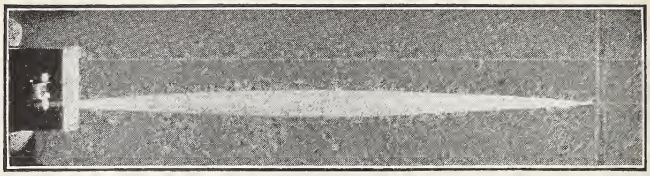


FIGURE 393

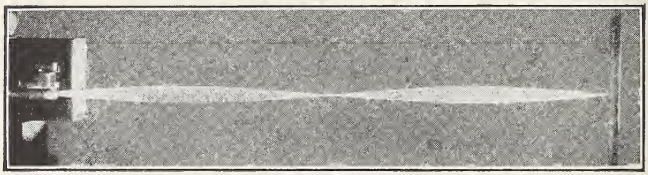


FIGURE 394

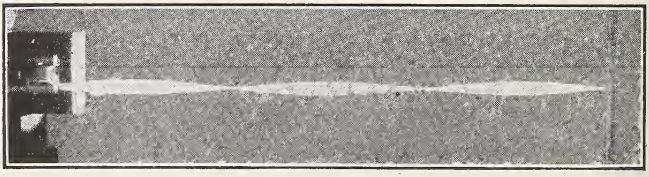


FIGURE 395

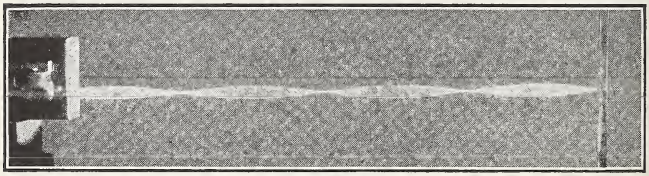


FIGURE 396

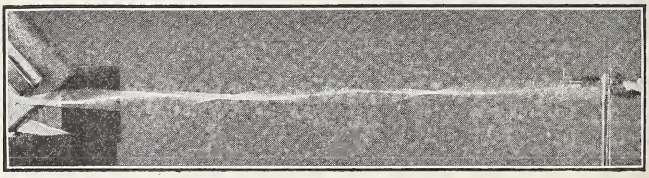


FIGURE 397

(*Copyright, Houghton Mifflin Company*)

overtones. Figure 397 shows a complex vibration of a string simultaneously vibrating with several loop formations, thus sending forth composite sounds consisting of a foundation tone and a number of overtones. A specific illustration of this effect is to compare the sound of D tuning fork with the note D played on a violin. (Refer to Figure 398.) The D tuning fork sends out a pure tone. The D string on the violin, however, not only sends forth its fundamental but also a number of overtones and harmonics in various degrees of prominence which give it tonal color. The combined effect, then, of playing the four tones, C, E, G, and C′ together, produces a fullness and richness in tone because of the presence of many beat tones and overtones. In the study of harmony it is called the *tonic chord.*

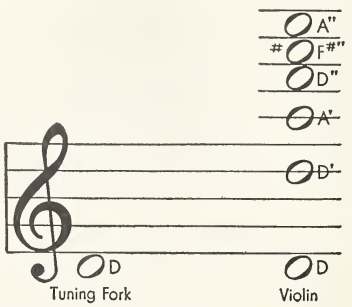


FIGURE 398
A violin tone includes a fundamental with many harmonics

The Major Diatonic Scale

The distinctly pleasing combination of tones that has been discussed in detail has long been referred to by musicians as the *major triad*, C, E, G, or the major tetrad, C, E, G, C′.

C		E		G		C′
264		330		396		528
4	:	5	:	6	:	8

The significant thing here is not the absolute frequencies of these tones, but the relative frequencies. Any four tones whose frequencies are in the ratio of 4 : 5 : 6 : 8, will be pleasing to the ear. The musical scale, the *do re mi* of our childhood days, is essentially a combination of major triads in the order shown below:

G	A	B	C	D	E	F	G	A	B	C′	D′
			4		5		6				
						4		5		6	
4		5		6			4		5		6
	220		264		330		396		495		594
198		$247\frac{1}{2}$		297		352		440		528	
Ratio			1	$\frac{9}{8}$	$\frac{5}{4}$	$\frac{4}{3}$	$\frac{3}{2}$	$\frac{5}{3}$	$\frac{15}{8}$	2	
Interval				$\frac{9}{8}$ step	$\frac{10}{9}$ step	$\frac{16}{15}$ half-step	$\frac{9}{8}$ step	$\frac{10}{9}$ step	$\frac{9}{8}$ step	$\frac{16}{15}$ half-step	
			Do	re	mi	fa	sol	la	si	do	

The fundamental frequency used for the above table is C = 264. The fun damental tone in the musical scale can have any frequency; the musica scale is the result of establishing certain *relative frequencies* between th various tones. Manufacturers of musical instruments in the United State have now agreed to take A = 440 as the standard musical pitch in thi country, and this is what gives Middle C a frequency of 264. The musica scale referred to above is called the *major diatonic scale.*

Scale of Equal Temperament

In many ways the piano can be considered the basic musical instrument From one standpoint, however, it has a serious mechanical disadvantage Its strings are fixed strings and there are only as many tones as pairs o strings. If musicians could express all their moods in the same musica scale based upon the same fundamental pitch of Middle C — that is always play in the key of C — the keyboard on the piano could be in th major diatonic scale. However, the composer who wishes to produce cer tain effects often will build his scale on foundation frequencies other tha that of Middle C, such as the key of E, with E = 330 as a fundamenta Then, on these new fundamentals, he builds other major diatonic scales This immediately makes it necessary to bring other pitches into the pian keyboard. However, it is mechanically impossible to build an instrumen with fixed strings which is usable and which will allow the musician to pla music written in any key he wants. This impasse led to a compromise, new scale called the *scale of equal temperament.* In this scale the octave i divided into twelve equal intervals between thirteen keys. Each note i

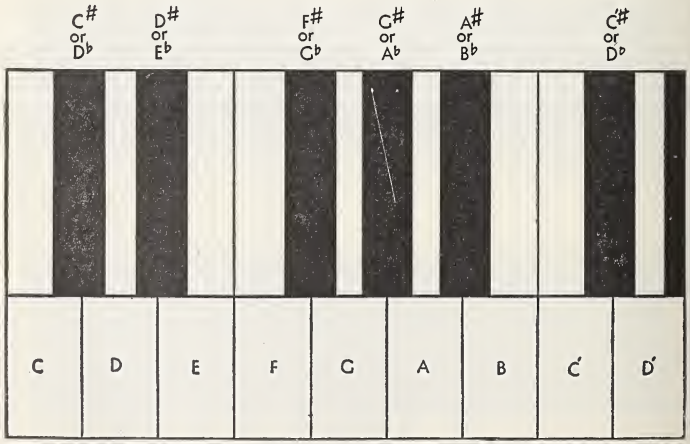


FIGURE 399. THE PIANO KEYBOARD — EQUAL TEMPERAMENT

this scale has a frequency 1.0595 times that of the preceding note. The last note in the scale will have a frequency $(1.0595)^{12}$, or two times the fundamental. Figure 399 shows the relationship between these various keys on the piano keyboard. A comparison of the major diatonic and the equally tempered scales will indicate to what extent the piano keyboard is a musical compromise. Thus, the major diatonic scale consists of eight tones and

	C	C♯ D♭	D	D♯ E♭	E	F	F♯ G♭	G	G♯ A♭	A	A♯ B♭	B	C′
Equally tempered scale	264	279.7	296.3	314	332.6	352.4	373.4	395.6	419.6	444	470.4	498.4	528
Diatonic or just tempered scale	264	—	297	—	330	352	—	396	—	440	—	495	528

seven intervals while the equally tempered scale consists of thirteen tones and twelve equal intervals. A violinist or a vocalist, if singing alone, can render music in the just tempered scale, but the pianist must often use tones that deviate from the just tempered scale by nearly one per cent as indicated in the table above. This difference is detectable by a trained musician, but hardly noticeable by the average person. The purist in music does not like the equally tempered scale, but if he continues to demand an instrument with strings of fixed length and not more than seven and one-third octaves which will allow him to play music in any key, it must be built in the equally tempered scale with a total of eighty-eight tones.

We have seen how sound can have unpleasant effects on an individual because of certain characteristics of the sound-emitting source. Thus, music may be good or bad because of the manner of its production. However, even the best of music as played may be ruined for the hearer because of interference effects due to faulty designs of auditoriums. A reflected sound wave when it returns to the hearer as a single sound is called an echo. In auditoriums of faulty design a particular sound wave may be reflected as many as a hundred times from various wall surfaces. The general prolongation of sound through a room due to multiple reflection is known as *reverberation*. For good audibility the time of reverberation in an auditorium should be from one to two seconds. If the time of reverberation is less than this, sound will often seem unnatural; if the period of reverberation is too great, sounds become unintelligible. To secure this optimum period of reverberation is a question of design of the auditorium itself and the selection of the materials to be used in the walls.

Musical instruments have many different forms. They can be classified most conveniently into three different types: (*a*) percussion, (*b*) string, and (*c*) wind instruments. Within each type there are many designs of instruments to furnish all the desired frequencies. Thus, the kettle drum, the

snare drum, and the triangle found in every orchestra are percussion instruments with very different frequencies. In general, there are three different ways to increase the frequency of a vibrating string: (*a*) reduce the length, (*b*) increase the tension, and (*c*) decrease the mass per unit of length. In the piano, for example, the high strings are made of short wires and thin cross sections under relatively great tension. The frequency range of any particular stringed instrument is determined by the length and mass per unit length of the strings. After the instrument is once made, tuning is then accomplished by controlling the tension on the strings. It is not so simple to account for the frequency characteristics of wind instruments. In general, air is set in vibration within an air column in a pipe or tube. It is true that the frequency of the sound from such a pipe *increases* as the length of the pipe *decreases*. Compare the length of a piccolo, for example, with a bass tuba. In most wind instruments the length of the vibrating air column can be controlled by the musician to change the frequency of the tones. In a trombone this is accomplished by means of a sliding tube; in a cornet, by valves. In the bugle or valveless trumpet, the frequency depends entirely on the manner in which the air column is made to vibrate and is controlled by the tension upon the lips.

SUMMARY

1. Noise consists of sounds of widely varying and continually changing frequencies.
2. A musical tone consists of sound of a single or predominant frequency in the audible range of the ear.
3. Three important characteristics of a musical tone are (*a*) pitch or frequency, (*b*) loudness, and (*c*) quality or timbre.
4. Loudness is a complex psychological reaction to sound and is a measure of the sensation produced on an individual by sound.
5. Loudness depends upon the simultaneous operation of two factors: (*a*) the energy carried by the sound waves to the ear, and (*b*) the frequency.
6. The average human ear is most sensitive to sounds with a frequency of about 2000.
7. The quality or timbre of a musical tone depends upon the number and prominence of overtones of the fundamental.
8. Music depends upon a blending of many tones of different frequencies. When two tones are played simultaneously, any of three principal results are possible:
   (*a*) The two tones may be in unison or the frequency of one may be a multiple of the other. This result is pleasant.

[1] The effect of these three factors is as follows:

$$F(\text{requency}) \propto \frac{1}{l(\text{ength})} \propto \sqrt{\frac{t(\text{ension})}{m(\text{ass})}}$$

(*b*) The two tones may result in beats which are unpleasant — dissonance. Beats are most unpleasant when they occur at the rate of 15 to 40 per second.

(*c*) The two tones may produce pleasant beats or difference tones.

9. A vibrating sound source — string, membrane, or air column — often vibrates in such a way as to send forth tones of frequencies 2, 3, 4, ...*n* times the fundamental frequency. These are called harmonics or overtones.

10. Tones, whose frequencies are in the ratio of 4:5:6, produce an especially pleasing effect on the ear because of a blending of many beat tones and overtones with the various foundation frequencies. This combination of frequencies is called the tonic chord or major triad.

11. A tone which is due to very frequent beats from two tones and whose frequency is a submultiple of one of the tones is called a beat or difference tone.

12. The major diatonic scale consists of eight tones and seven intervals with frequencies $\frac{9}{8}$, $\frac{5}{4}$, $\frac{4}{3}$, $\frac{3}{2}$, $\frac{5}{3}$, $\frac{15}{8}$, and two times the fundamental tone.

13. The scale of equal temperament consists of thirteen tones and twelve intervals all of which are alike. The scale of equal temperament is a musical compromise necessary to make the piano a practical instrument.

14. Musical instruments are classified as three principal types: (*a*) percussion, (*b*) string, and (*c*) wind.

STUDY EXERCISES

1. Indicate whether the following statements are true (T) or false (F):

.... The audibility of a sound depends only upon the energy of the wave — amplitude of vibration.

.... The range of frequency of the human voice is from 20 to 20,000 vibrations per second.

.... The range of frequency of audible sound is 20 to 20,000 vibrations per second.

.... A musical tone consists of one or more sounds of regular and constant frequencies.

.... A noise consists of sounds that are of irregular and erratic frequencies.

.... The musical scale consists of notes that have frequencies that bear a definite relationship to some fundamental note, as middle C= 256.

.... Two notes whose frequencies are in the ratio of 2:1 represent an interval of one octave.

.... It is possible for a violinist with a keen sense of pitch to play music in the major diatonic scale.

.... A skilled musician can play music in the major diatonic scale on an ordinary piano.

.... Musical tones of high frequency travel faster through air than notes of low frequency.

.... It is impossible to get a note of such high frequency that it cannot be heard.

2. Associate by number the terms at the right with the appropriate statement given below:

.... Two notes which are unpleasant when sounded together illustrate .....

.... The major chord which is such a prominent part of all music consists of .....

.... A middle C fork when sounded sets the middle C string of a harp to vibrating. What does this illustrate?

.... A musical tone often represents a pleasing fusion of various sounds which have a definite frequency relationship to each other. What name is applied to the most prominent sound?

.... That term in connection with sound which corresponds to color in light.

.... Two notes which produce a pleasing combination when sounded together illustrate ....

.... That two notes are not quite in unison can be detected by listening for what?

.... A note with a frequency of 256 when sounded simultaneously with a note of frequency 384 will result in a note with a frequency of 128, the octave below 256. This is called a .....

.... Middle C (256), when sounded on a violin, consists of various sounds, among them a note with a frequency of 512. This is called a .....

1. Fundamental
2. Beats
3. Beat tone
4. Overtone or harmonic
5. Three notes whose vibration ratios are 4:5:6
6. Three notes whose vibration ratios are 10:12:15
7. Pitch
8. Sympathetic vibration
9. Dissonance
10. Consonance

3. Certain numbered strings on a harp have frequencies as follows:

(1)	(2)	(3)	(4)	(5)	(6)	(7)
200	250	300	400	500	600	800

When various combinations of these strings are played simultaneously, certain sound effects are produced which are referred to by the numbered expressions at the right. Associate by number the appropriate term that best describes the result that would be obtained by playing the following strings simultaneously:

.... 1 and 4	.... 4, 5, and 6	1. Octave
.... 1, 2, and 3	.... 2 and 6	2. Major chord
.... 4 and 5	.... 2 and 3	3. Beat tone
.... 2 and 5	.... 3 and 6	4. Consonance
.... 4 and 7	.... 1 and 3	5. Dissonance

FOR FURTHER READING

1. Jeans, J. H., *Science and Music.*

An unusually good presentation of the science of music for the general reader. The following pages are recommended: 17–59, pure tones and simultaneous sounds; 61–106, harmonic tones in strings; 123–151, different types of musical instruments; 154–190, harmony and musical scales; 189–215, acoustics of rooms; 217–252, the ear as an interceptor of sound.

2. Miller, D. C., *The Science of Musical Sounds.* New York: The Macmillan Company, 1944.

This is by one of the world's authorities on sound and music. There are many remarkable photographs of the effects of sound waves. Technical knowledge is not necessary in order to enjoy the book. Recommended for both musicians and non-musicians.

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The Eyes of Science

MOST OF THE INFORMATION that has been collected concerning our surroundings and the universe has been obtained by use of the eyes. But it is also true that much of our present information has been accumulated because man has learned to build instruments that can penetrate into space where the eye alone cannot see, and that also can reveal objects too small to be seen by the naked eye. Without the telescope, for example, our knowledge of even the closer planets would be very meager indeed, for they would then be mere bits of light in the heavens, bright enough only to reveal their movements along the ecliptic. The planets beyond Saturn would still be undiscovered; the rings of Saturn and the polar cap of Mars could not be seen. The only satellite that we should know anything about would be our moon. We would, in fact, still have a very meager conception of the nature of the universe. And where would we be without the microscope? This instrument is indispensable to reveal structures that the eye cannot see, as in the study of plant and animal tissue, bacteria, textiles, rocks and minerals, and metals and their alloys. In addition, we have a large group of optical instruments, including cameras, field-glasses, range-finders, and motion-picture machines, whose existence depends upon our present knowledge of lenses. It will be the purpose of this chapter to discuss certain laws and phenomena concerning light which have important applications in the construction of various optical instruments.

The Velocity of Light

We are all prone to regard the velocity of light as instantaneous. It was so regarded by the ancients, but there have always been a few bold spirits who could not conceive of anything traveling in space from one point to another in "no time at all." Galileo unsuccessfully attempted to measure the velocity of light by sending a signal from a lantern on one hilltop to observers on a distant second hilltop, who returned another signal with another lantern. With the crude time-measuring devices available in Galileo's time it was impossible to measure the small interval of time required for the light to travel to and fro between the two stations. In any method for measuring the velocity of light, data for the following relationship must be collected:

$$v(\text{elocity}) = \text{distance covered in one unit of time} = \frac{d(\text{istance})}{t(\text{ime})}$$

If the assumption is made that light travels with uniform speed and that it far transcends the velocities of any ordinary moving objects, there can be only two methods to measure the velocity of light experimentally. One possibility is to use ordinary methods for measuring time — common accurate clocks — and to get a measurable time interval by making the distance between two observation stations very large. The second method is to develop special, precise methods of measuring time intervals as small as 1×10^{-6} seconds and then to use observation stations relatively close together. Either procedure should be able to provide experimental data for the determination of the value of the ratio d/t, which is the velocity.

When time-measuring devices were relatively crude, only the first method could be used to demonstrate that light has a measurable velocity. It was a brilliant young Danish astronomer, Ole Roemer, who first was keen enough to use observation and signal stations in astronomical space. The logic underlying his method should be apparent from Figure 400. In Roemer's method the observation station was on the earth, and the signal station was one of the moons of Jupiter. The time required for this moon to complete its orbit around Jupiter was known accurately. When the earth was in position E_1 with respect to the sun, the time that the moon would be eclipsed by Jupiter was accurately observed. Six months later the earth was in position E_2. If the velocity of light were actually instantaneous, the time that the same moon would be eclipsed could be accurately predicted. Actual observation showed, however, a time lag of about a thousand seconds between the predicted and the actual time of eclipse. Roemer correctly attributed this time lag to the additional time required for light to travel across the diameter of the earth's orbit, which we now know is 186,000,000 miles. Hence,

$$v = \frac{d}{t} = \frac{186{,}000{,}000}{1{,}000 \text{ seconds}} = 186{,}000 \text{ miles/sec.}^1$$

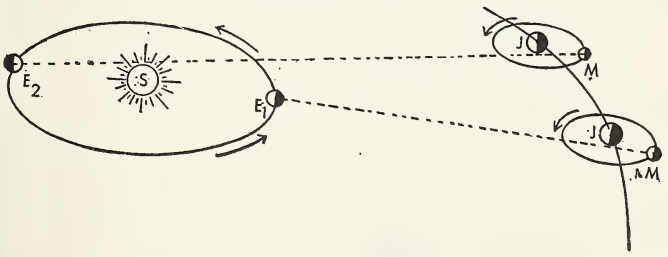

FIGURE 400. ROEMER'S METHOD FOR MEASURING THE VELOCITY OF LIGHT

[1] This figure is not the one given by Roemer, but is based upon modern data. We now know that Roemer's result was 25 per cent too low because of errors in the data he had to use. However, the reasoning back of Roemer's method was sound, and his result was a first indication of the enormous velocity of light.

This corresponds to a distance of about seven and a half times the earth's circumference in one second. Many of Roemer's compeers were inclined to be skeptical, but his data were amply confirmed when precise methods for the measurement of a very small time interval were finally devised by such experimenters as Fizeau, Foucault, and Michelson, who found it possible to measure the velocity of light between stations upon the earth itself.

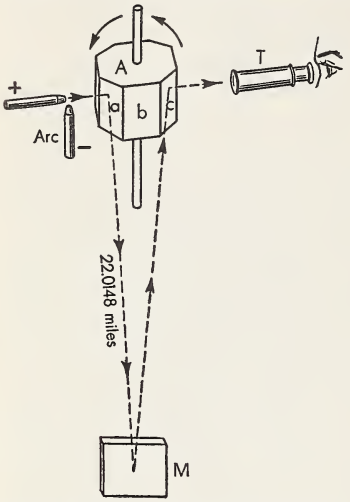

FIGURE 401. MICHELSON'S METHOD FOR MEASURING THE VELOCITY OF LIGHT

The essence of Michelson's method is diagrammed in Figure 401. A was an octagonally shaped wheel with a mirror in each face and with a provision for revolving at various constant speeds known in terms of revolutions per second. The mirror M was so placed on a distant mountain that light from the arc could be seen in the telescope T with A stationary. The wheel A was then set in rotation, and the light from the arc would pass from the field of view in the telescope. As the speed of rotation was slowly increased, a point would finally be reached where, while the light was traveling a distance of 2×22.0148 miles, the face b would make one-eighth of a turn and be in position c when the light beam returned. Under these precise conditions the light from the arc would again be seen in the telescope. Thus, the time interval needed for the light to travel between two stations and return could be found to a high degree of precision. The data from such an experiment read as follows:

$$\text{Distance light traveled} = d = 2 \times 22.0 \text{ miles}$$

$$\text{Revolutions per second} = 527.5$$

$$\text{Time for light to travel to and fro} = t = \frac{1}{(8)(527.5)}$$

$$t = \frac{1}{4220} = .000237 \text{ sec}$$

Then,

$$v = \frac{d}{t} = \frac{2 \times 22.0}{.000237} = 186{,}000 \text{ mi/sec}$$

After very careful attention to overcoming many experimental difficulties and after a lifetime of effort, Michelson's final results for the velocity of

light in a vacuum were 186,245 mi/sec, or 299,776 km/sec. The latter quantity is deemed to be precise to within 4 km/sec — a truly remarkable achievement. Michelson was America's first winner of the Nobel Prize in Physics. For ordinary calculations involving the velocity of light, the velocity is taken to be 186,000 mi/sec, or 3×10^{10} cm/sec.

Light Can Be Reflected

Light obeys the same law of reflection that was found to govern water waves and sound: the angle of reflection is equal to the angle of incidence. In Figure 402 light rays from *S* make an angle *i* with the perpendicular to the surface of the mirror *MM'*. Experimentally it is found that the reflected rays OS'' make an angle *r* with the perpendicular, which is equal to angle *i*. The reflected light rays apparently originate at S' in the rear of the mirror. In reflection from a plane mirror the image appears to be as far behind the mirror as the object is in front of the mirror. The image, furthermore, is erect but reversed from right to left. (Refer to Figure 403.) Mirrors are often used to line the walls of public halls to produce an illusion of great depth and size.

Light Can Be Refracted

A straight stick partly immersed in water appears to be bent where it enters the water. Anyone can try the experiment with a pencil in a glass of water. In Figure 404 the fish appears to be at *H* and the bottom of the stream appears to be at *I*. Light rays *FO*, traveling from the fish, undergo a change in direction (*OE*) as they emerge into air. *SO* is a perpendicular to the surface of the water at *O*, where the light ray emerges. The angle *i* is the angle of incidence, and the angle *r* made by the refracted ray *OE* and

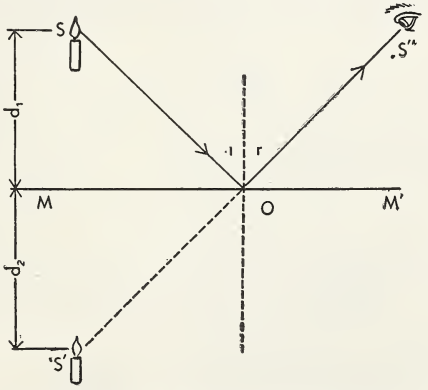

FIGURE 402. THE LAWS OF REFLECTION

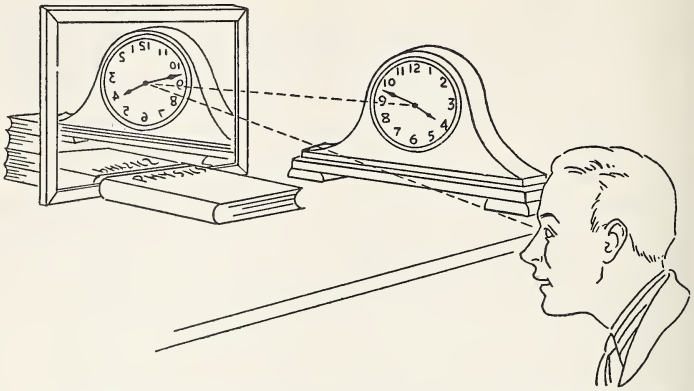

FIGURE 403. THE RELATION OF IMAGE TO OBJECT IN REFLECTION

the perpendicular is the angle of refraction. Note that angle *r* is greater than angle *i* when light passes from the more dense medium water into air. In other words, under these circumstances the refracted ray is bent away from the perpendicular *SO*. Conversely, when light passes from air — the less dense medium — into water, the refracted ray is bent toward the perpendicular.

Light rays, in passing obliquely from one transparent substance into another transparent substance of different density, always undergo a change in velocity and a change in direction. This phenomenon, as we have seen, is called *refraction*. Thus, the light rays that traverse a piece of plate glass are definitely displaced. (Refer to Figure 405.) The light ray *AO* on entering the glass is bent toward the perpendicular; that is, *OE* approaches *PO*. When the ray *OE* passes from the glass into the less dense

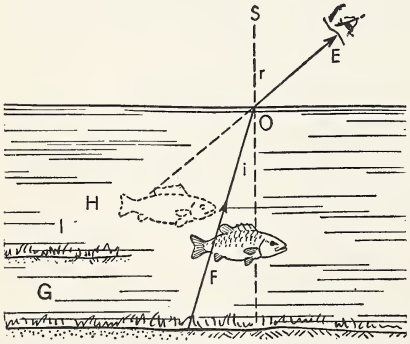

FIGURE 404. REFRACTION OF LIGHT

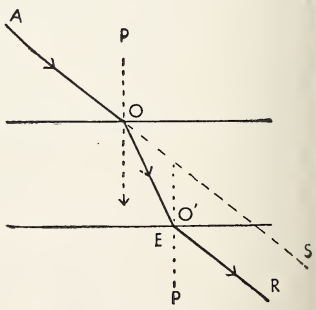

FIGURE 405. REFRACTION OF LIGHT THROUGH PLATE GLASS

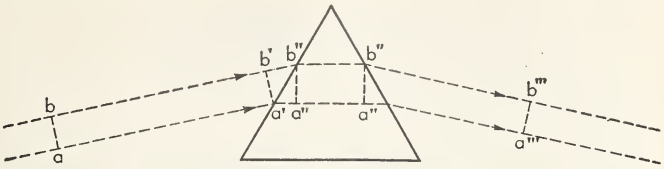

FIGURE 406. BENDING OF LIGHT RAYS PASSING THROUGH A PRISM

air, the emergent ray *ER* is bent away from the perpendicular *PO'*. If the sides of the glass are parallel, the ray *ER* is also parallel to *AO*.

The Eyes of Science

Any optical instrument depends upon the effect of lenses on light. The functioning of a common lens can be explained by considering the refraction of light through a glass prism. (Refer to Figure 406.) Thus, light originating at *ab* will travel in parallel paths to the prism. Here one side of the wave front (*a'*) will enter the glass first and will then travel more

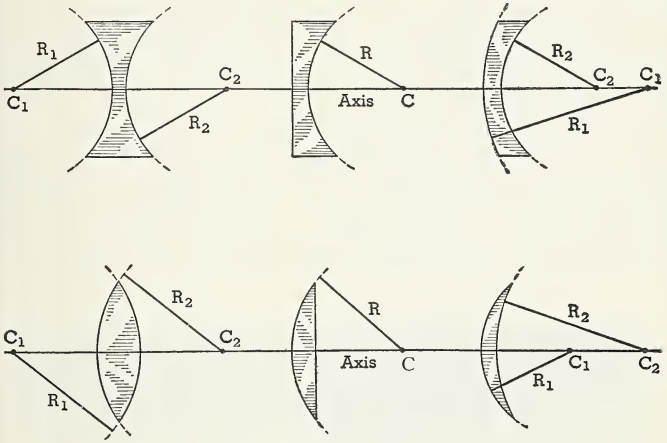

FIGURE 407

ABOVE. DIVERGING LENSES: DOUBLE CONCAVE, PLANO-CONCAVE, CONVEXO-CONCAVE

BELOW. CONVERGING LENSES: DOUBLE CONVEX, PLANO-CONVEX, CONCAVO-CONVEX

(From Clark, Gorton, and Sears, "Physics of Today" published by Houghton Mifflin Company)

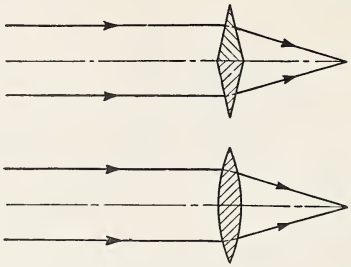

FIGURE 408 (*a*)
COMPARISON OF TWO PRISMS
WITH A BI-CONVEX LENS

slowly, because of the effect of the denser medium. The part of the beam still in air (b') will travel relatively faster. Hence, the wave front changes its direction of travel as it enters the prism. The student can verify for himself that the light rays are bent toward a perpendicular to the glass surface as they enter the glass. The side of the wave front (b'') will be the first to emerge into air at the other side of the prism; it then begins to travel faster. Hence, while the wave front $a''b''$ is emerging into air, there will again be a change in direction of the wave front $a'''b'''$. The significant observation here is that the light undergoes two changes in direction and that it is bent toward the base of the prism.

If the above experiment is performed with two prisms base to base, the light rays can be made to *converge*. (Refer to Figure 408, *a*.) Parallel light rays may be made to *diverge* if the two prisms are placed apex to apex. (Figure 408, *b*.) The lenses which are such an essential part of many optical instruments function either by diverging or converging light rays. There are six types of spherical lenses, three converging and three diverging. Figure 407 illustrates these types in the following order: double convex; plano-convex; concavo-convex; double concave; plano-concave; and convexo-concave.

Converging lenses are invariably thinner at the edges than in the center, whereas diverging lenses are always thicker at the edges than in the center. Their action on a beam of light is shown in Figures 409 and 410. Note that in Figures 408, *a*, and 409, the light rays are brought to focus at a point. This is called the *principal* focus. The distance of the principal focus from the lens, called the *focal length*, is an important characteristic of a lens. The numerical value of this constant for any lens is determined by the nature of the glass and the curvature.

Bi-convex lenses have two principal uses: (1) to produce a real image o

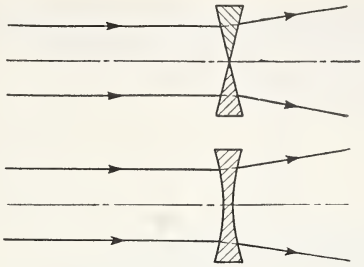

FIGURE 408 (*b*)
COMPARISON OF TWO PRISMS
WITH A BI-CONCAVE LENS

some object on a screen, retina of the eye, or on a photographic film; and (2) to function as a magnifying glass. Figure 411 illustrates the use of a bi-convex lens to produce a real image. Here the object AB must be located at a distance greater than the focal length of the lens. The light rays from AB, after passing through the lens, are made to converge to form a real *image* at $A'B'$, which is *inverted*. It is called a *real image* because it can be viewed on a screen. The images obtained with the eye, the lens of a camera, motion-picture projector, and telescope are real images and inverted. The image on a motion-picture screen is right side up because the film is placed in the machine right side down.

The principles involved in the common magnifying glass are shown in Figure 412. AB represents any object so close to the lens L that it is inside the principal focus F. The image must be viewed with the eye close to the lens. It appears at $A'B'$ as an *enlarged*, *erect* image. This kind of image

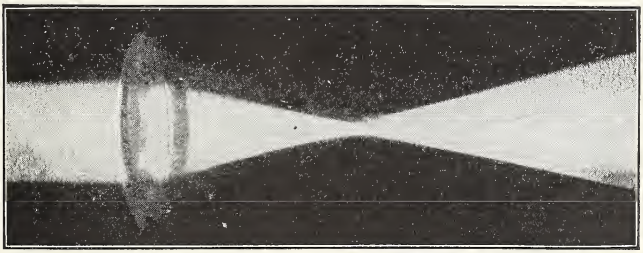

FIGURE 409. CONVERGING A BEAM OF LIGHT WITH A CONVEX (CONVERGING) LENS

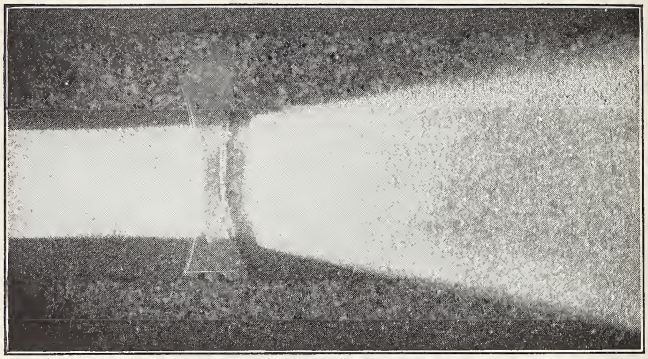

FIGURE 410. PARALLEL RAYS OF LIGHT ARE MADE TO DIVERGE WITH A CONCAVE (DIVERGING) LENS

must be seen with the eye through the lens, since it cannot be projected o a screen. It is called a *virtual* image. The use of a bi-convex lens to pro duce a real image and as a magnifying glass can be demonstrated with common reading glass. If printed material is viewed through the glas with the eye relatively far from the lens, the type will appear inverted When the eye approaches sufficiently close to the glass, the type will ap pear erect and enlarged. The erect image is a virtual image. The inverte image is a real image. A better conception of a real image is obtained b holding a reading glass two or three feet from an electric light bulb. B carefully bringing up a sheet of paper on the side of the reading glass oppo site the bulb, the inverted image of the light bulb can be brought to a focu on the paper.

A very common application of converging and diverging lenses is foun in ordinary spectacles. A near-sighted person, for example, cannot see dis tant objects clearly because the lens of the eye brings the image in focus i front of the retina. This defect is corrected by a diverging lens. (Refer t

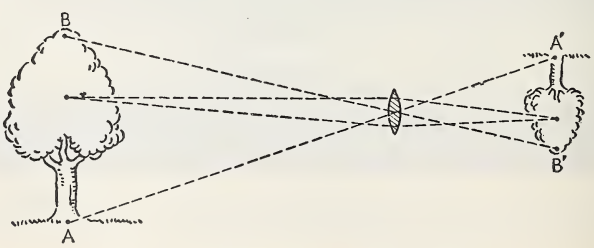

FIGURE 411. THE PRINCIPLE OF THE LENS

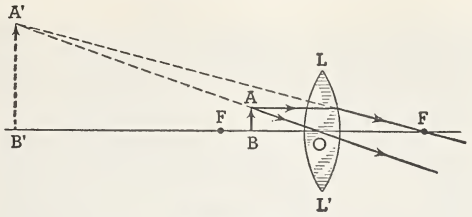

FIGURE 412

The object distance is less than OF. Is the image real?

Figures 413 and 414.) A far-sighted person cannot distinctly see objects near at hand because the lens of the eye brings the image in focus back of the retina. This condition can be corrected with a converging lens. (Refer to Figures 413 and 415.)

Very important applications of lenses are found in the telescope and microscope. The principle of the *refracting telescope* is shown in Figure 416. The objective lens MN is in one end of a tube of such length that the light rays that enter it are brought to a focus at $A'B'$ inside the principal focus of the eyepiece E. Both the objective and eyepiece are convex (converging)

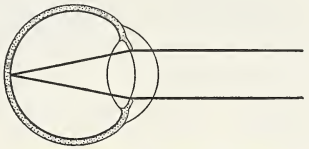

FIGURE 413. A NORMAL EYE

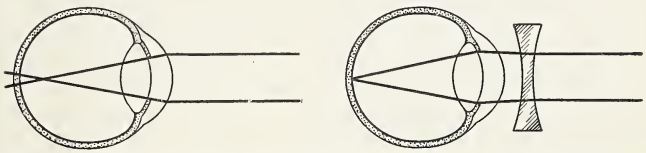

FIGURE 414. A NEAR-SIGHTED EYE CORRECTED BY A DIVERGING LENS

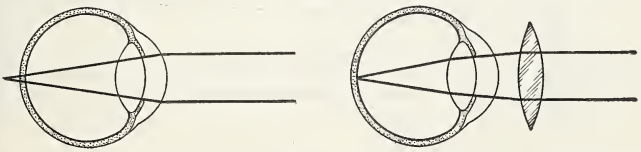

FIGURE 415. A FAR-SIGHTED EYE CORRECTED BY A CONVERGING LENS

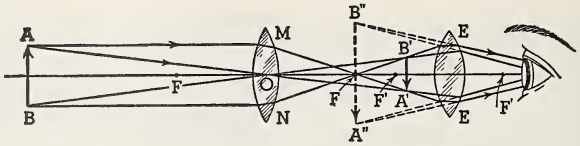

FIGURE 416. A DIAGRAM OF A REFRACTING TELESCOPE

lenses. The eyepiece E functions as a common magnifying glass and en larges the real image, $B'A'$, to produce the final image $B''A''$, which is in verted. However, the object is always at a great distance, and hence th image must always be smaller than the object. In order to get the imag as large as possible, the focal length of the objective lens must be made ver large. This, of course, means that the objective lens must be mounted in relatively long tube, which leads to mechanical difficulties. But there is second difficulty: in order to observe a distant object, it is necessary to ge as much light as possible, and this can be done only by increasing the diam eter of the objective lens. These two factors combined make powerfu refractors very difficult and expensive to build. The refractor of th Yerkes Observatory is the largest ever built; it has an objective lens fort inches in diameter and a focal length of sixty-four feet. The photograph of the moon shown on pages 284, 292 were taken with the Yerkes refractor

Astronomical telescopes now being built are *reflecting* telescopes. Ligh in being reflected from curved surfaces obeys the same law of reflection a from a plane surface. (Refer to page 771.) Light rays can be made to con verge with a concave mirror. The principle of one design of reflecting tel escope is shown in Figure 417. The light rays from a distant object ar made to converge to a focus by a concave parabolic mirror M. A righ angle prism mn turns the light through an angle of ninety degrees and as i the refracting telescope produces a real image inside the principal focus o the eyepiece E. This image is further magnified by the eyepiece E. Thi particular design for a reflecting telescope is another of the contributions o Sir Isaac Newton. (Refer to Figure 417.) A second type of reflecting telescope the Cassegrainian, uses a mirror to reflect the focused rays back throug a small opening in the middle of the mirror itself, to the viewing eyepiece

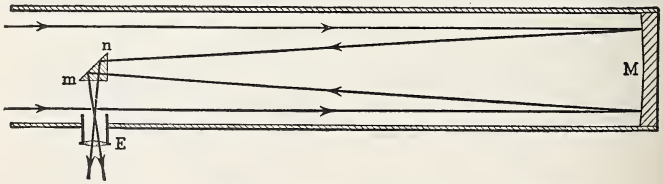

FIGURE 417. A DIAGRAM OF A REFLECTING TELESCOPE

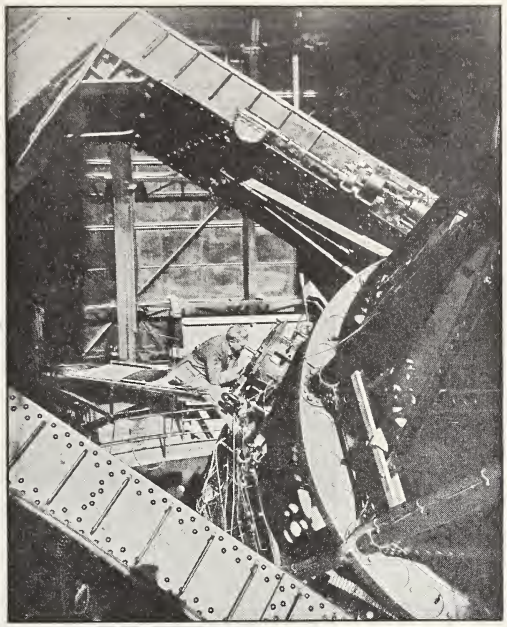

FIGURE 418. OBSERVER AT THE CASSEGRAIN FOCUS OF ONE HUNDRED INCH TELESCOPE OF MOUNT WILSON OBSERVATORY
(*Courtesy of Mount Wilson Observatory*)

The microscope is essentially a train of two converging lenses. (Refer to igure 419.) The object is placed beyond the principal focus of the ob-ective lens O, and the image from the first lens is formed inside the prin-ipal focus of the eyepiece E to produce a second image, enlarged and vir-ual. The second image is inverted because the first real image was in-erted. The object lens O, then, serves to produce a real inverted image $'B'$. The eyepiece E serves as a simple magnifying glass to produce an nlarged virtual image $A''B''$ of the first image. Modern microscopes of igh power always consist of more than one lens in the objective, and this likewise true of the eyepiece. (Refer to Figure 420.) By a suitable com-ination of objective lenses and eyepieces a magnifying power as great as vo thousand may be obtained. The modern microscope finds many appli-ations, one of the most important of which is the diagnosis of certain dis-ases by isolating and identifying the organism causing the disease. Ty-hoid, anthrax, diphtheria, cholera, and tuberculosis are among the dis-ases caused by organisms readily identified under the microscope. Simi-

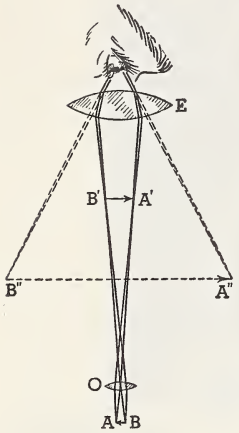

FIGURE 419
A DIAGRAM OF THE
COMPOUND MICROSCOPE

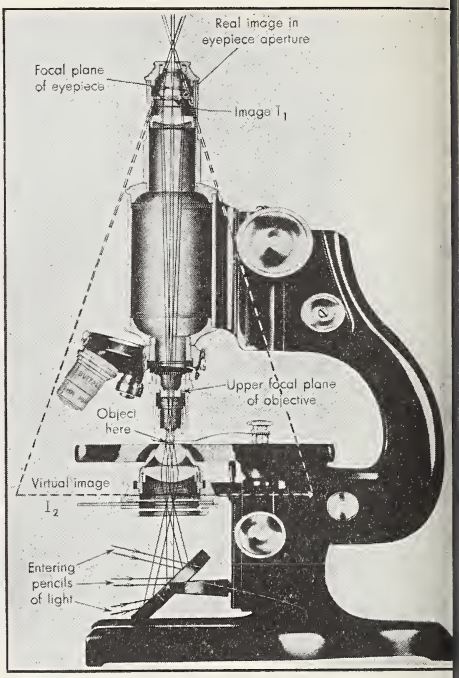

FIGURE 420
THE OPTICS OF A COMPOUND MICROSCOPE
(*Courtesy of Spencer Lens Company, Buffalo, N.Y.*)

larly, the chemist finds the microscope indispensable in the study of textile and of metals and their alloys. The geologist uses it to study rocks an minerals.

SUMMARY

1. Roemer, a contemporary of Newton, devised the observational method whic gave the first indication of the enormous velocity of light.
2. Michelson, an American, perfected a method for accurately measuring ex tremely small intervals of time, and thus he was able to measure with grea precision the velocity of light between observation stations on the earth.
3. Light travels at the enormous velocity of 186,000 mi/sec, or 3×10^{10}cm/sec.
4. The law of reflection states that the angle made by a light ray and a perpen dicular to the surface (angle of incidence) is equal to the angle of reflectio This is true for reflection from plane or curved surfaces.
5. A virtual image is one that can be seen with the eye, but cannot be projecte upon a screen; it is erect.

6. In reflection from plane surfaces, the image is virtual, erect, and reversed. The image is apparently as far in back of the reflecting surface as the object is in front of it.
7. In passing from one substance into another at an angle, light rays always undergo a change in velocity and direction. The velocity is less in the denser medium. This phenomenon is called refraction.
8. Light, in passing from a less dense into a more dense medium, is bent toward a perpendicular to the surface between the two mediums. The converse is true for light passing from a more dense to a less dense medium. This is the important Law of Refraction.
9. In passing through a triangular prism, light rays are deviated toward the base of the prism.
10. Converging lenses are used to converge light rays.
11. Diverging lenses are used to diverge light rays.
12. A real image is one that can be projected upon a screen; it is inverted.
13. A converging lens brings parallel light rays to a point called the principal focus. The distance of the principal focus from the lens is called the focal length.
14. A converging lens is used (*a*) to produce a real inverted image and (*b*) to function as a magnifying glass. When used to produce a real image, the object must be located beyond the principal focus. When used as a magnifying glass, the object must be inside the principal focus, and the image is always erect, enlarged, and virtual.
15. The following facts concerning refracting telescopes are significant: (*a*) the objective lens produces an inverted real image of the object inside the principal focus of the eyepiece; (*b*) the eyepiece functions as a common magnifying glass and enlarges the real image produced by the objective lens; (*c*) mechanical and engineering difficulties set a limit to the size of refracting telescopes.
16. Reflecting telescopes are of two principal types: (*a*) Newtonian, and (*b*) Cassegrainian. The light rays are brought to a focus with a parabolic mirror. Reflecting telescopes can be made in much larger sizes than refracting telescopes.
17. Microscopes have a train of two converging lenses. The object is placed beyond the principal focus of the objective lens, which produces a real image, and this is thrown inside the principal focus of the eyepiece, which functions as a magnifying glass. The image is always enlarged.

STUDY EXERCISES

1. A book received ample illumination at a distance of sixteen feet from a light fixture which contained four light bulbs. How far from the light should the book be placed to be equally well illuminated if only one light bulb is operating? Review the inverse square law for light, page 329, before attempting a solution.
2. An astronomer made the statement that the sun can really be seen before it gets above the horizon. What did he mean? What property of light is involved? Explain.

3. Make a drawing showing the relative positions of the sun, earth, and moon during the first quarter. Indicate the path of the light from sun to observer which causes the new crescent moon. Likewise indicate the path of the light which makes visible the part of the moon which is not directly illuminated by the sun. This exercise illustrates what characteristic property of visible light?
4. Hold a pencil before a sheet of paper and close to an electric light. Hold the pencil close enough to give a sharp shadow. Verify the fact that the shadow gets less distinct as the paper is moved farther from the pencil. Is this due to reflection, refraction, diffraction, or interference of light? Explain.
5. Consider an ordinary magnifying or reading glass. Is it a concave or convex lens?

   Hold the glass at right angles to the rays from the sun in front of a piece of paper. Move the paper back and forth until the rays of the sun are concentrated in a fine point. How do you account for the result? What term is applied to this unique distance from the lens?

   If the glass is held close to a printed page, describe the image as to the following characteristics: Enlarged or reduced, real or virtual, erect or inverted.

   Hold the glass about five inches from a printed page and describe the image as to the following characteristics: Enlarged or reduced, real or virtual, erect or inverted.
6. With an apparatus like that described in Figure 401, the intensity of the light when viewed in the telescope was a maximum when the mirror with eight faces was rotating 1160 times per second. The distance from the rotating mirror to the stationary mirror was 10.0 miles. What is the velocity of light from this experiment?

FOR FURTHER READING

1. LEMON, H. B., *From Galileo to the Nuclear Age.*
   Chapter 39 deals with visible light.
2. JENKINS, F. A., and H. E. White, *Fundamentals of Physical Optics.* New York: McGraw-Hill Book Company, 1937.
   An excellent description of the mechanical ingenuity needed to measure the enormous velocity of light and the theory back of the principal methods.
3. EYRING, C. F., *Survey Course in Physics.*
   Light as energy, its velocity, and phenomena dependent on reflection and refraction are discussed in Chapter XII. Those phases of light necessary to understand optical instruments and their construction and uses are clearly presented in Chapter XIV.
4. BRAGG, WILLIAM, *The Universe of Light.* New York: The Macmillan Company, 1934.
   The author is a Nobel prize winner and an outstanding modern scientist. He presents the whole subject of light in language that is devoid of scientific terms and is very readable. Chapter II is concerned with optical instruments, including the eye.

44

What Is Light?

THE QUESTION "WHAT IS LIGHT?" has intrigued man ever since he began reflecting seriously upon his environment. The problem of the nature of light has engaged the earnest attention of many of our greatest scientists — including Newton, Huygens, Fresnel, Young, Michelson — but no complete answer has yet been found to the question. The many experiments that have been devised and performed to find an answer have enormously increased our knowledge of light, but the true nature of light is still unknown. Sir Isaac Newton was certain that light consisted of small particles — he called them *corpuscles*. An American, Arthur Compton, received the Nobel Prize in physics in 1927 for his experiments which indicated that light consisted of *photons*, another name for particles of light. In the long interval between Newton and Compton, the theory of light which had the confidence of scientific workers held that light was a form of *wave motion*. The struggle that has taken place between the wave theory and the particle theory of light is an admirable illustration of two of the most important functions of a theory: to serve as a guiding principle or method for conveniently organizing a mass of observational and experimental fact-material so as to make it as useful as possible, and to point the way to further discoveries. Without the wave theory of light it is quite likely that we would still be without the radio. It was the wave theory of light that enabled scientists to fathom the mysteries of the sun, the stars, and the rest of the universe by deciphering the "messages in code" that come to the earth from outer space on beams of light.

The first comprehensive treatise on light was Newton's *Optics*, published in 1704, in which he affirmed the corpuscular theory of light without specifying the characteristics of the corpuscles. A contemporary of Newton's, Huygens in Holland, championed the wave theory of light. In considering the velocity of light in water, these two conceptions led to divergent results. On the basis of Newton's corpuscular theory, light ought to travel faster in the denser medium, while the theory of Huygens indicated that light should travel more slowly in water.

Here was need for a crucial experiment — the comparison of the velocity

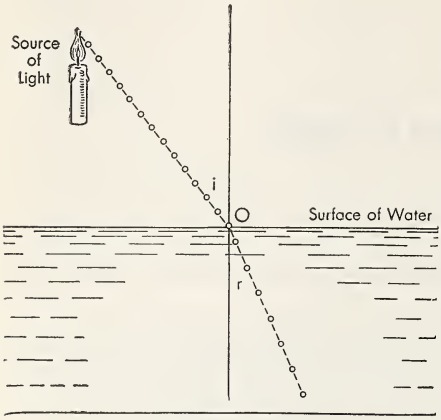

FIGURE 421.
NEWTON'S CONCEPTION OF REFRACTION

of light in water and in air — to decide between the two theories. The slowness that often marks the advancement of knowledge is indicated by the lapse of over 150 years before the experimental values were finally determined. Fizeau and Foucault (*ca.* 1850) experimentally proved that the velocity of light in water is three-fourths of its velocity in air, and thus verified Huygens' expression for the index of refraction of water. Thus there finally came direct experimental refutation of Newton's corpuscular theory.

Light as Waves on an Ether Sea

In the meantime workers like Young in England and Fresnel in France, during the early part of the nineteenth century, had effectively demonstrated diffraction, interference, and reinforcement effects from light which they were unable to explain without the wave conception. Diffraction effects with light are now known to be common. (Refer to page 737.) Light will actually bend around corners and penetrate into a shadow. A common example of diffraction can be seen in the shadow of a needle behind a strong light. If light did not undergo diffraction, the shadow would have sharp, distinct edges. Instead, the edges of the shadow are fuzzy. A careful examination of the shadow will reveal parallel light and dark lines within the shadow. Under certain circumstances, it is possible to find a bright line through the middle of the shadow. (Refer to Figure 423.) A very interesting variation of this experiment is to look at a bright, white surface or an open window through a narrow slit between two fingers held

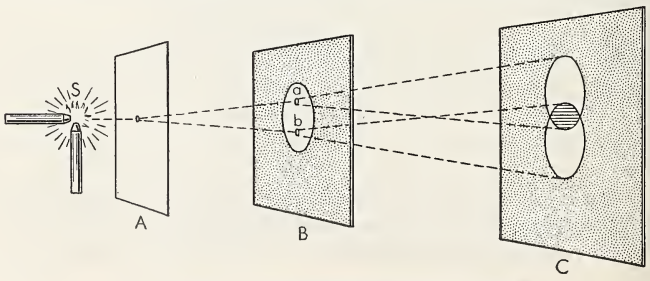

FIGURE 422. INTERFERENCE WITH LIGHT

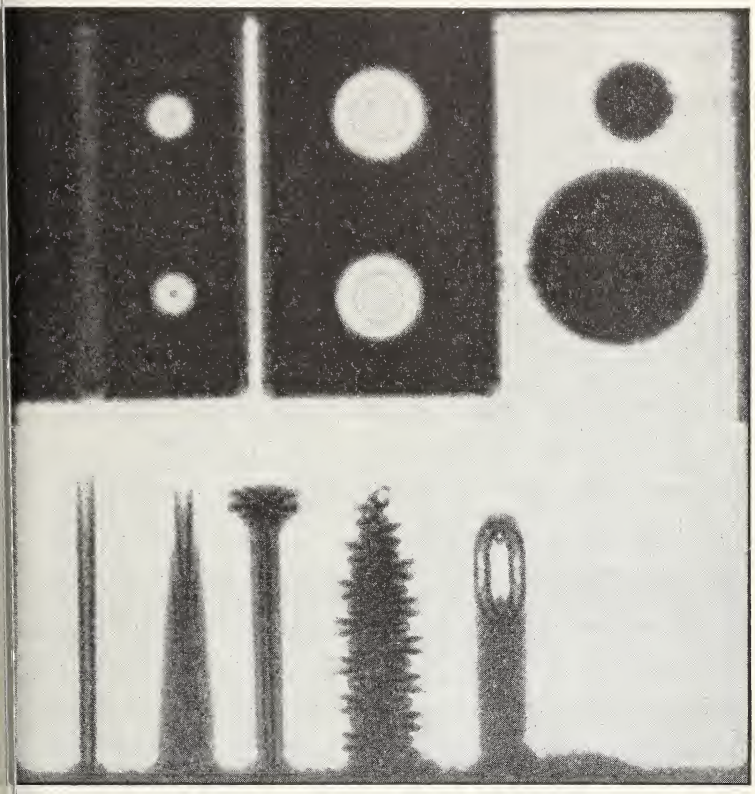

FIGURE 423. DIFFRACTION OF LIGHT

The spreading of light around the edges of some common objects is clearly revealed in s photograph. These effects were caused by light passing through or around two narrow ts, four circular openings of various sizes, two small disks supported by thin wires, two edles, a pin, a wood screw, and the head of a needle. (From "A Survey of Physics," by ederick A. Saunders, published by Henry Holt and Company. Used with permis- n of author and publisher)

close to the eye. By properly varying the width of the opening, with the hand about four inches in front of the eyes, it is possible to see, not a single band of light, but alternate light and dark lines. These lines are the result of diffraction followed by interference. The discovery of diffraction phenomena in the behavior of light has strengthened the wave theory of light.

Even more convincing evidence for the wave theory of light came in about 1803 with the work of Thomas Young, a London physician, who first demonstrated conclusively its interference phenomenon. In effect, Young used light with light to get darkness — lack of light. Some of his crucial experiments were extremely simple. For example, light from an intense light source S may be allowed to fall on a screen with a small opening (Figure 422). The resulting cone of light can be allowed to fall on a second screen B which has two small apertures a and b. In accordance with Huygens' principle stated on page 738, a and b will serve as two new independent sources of light waves which form two new cones of light which will fall on the screen C. If the distance of screen C from screen B is properly controlled, the two cones of light will overlap. Where this happens, there will be observed *alternate bright and dark lines*, which is evidence for constructive and destructive interference.

An experiment very similar to Young's crucial experiment can be easily performed by the student. Place a soap film on a loop of wire and hold it vertically to reflect light. In a short time the face of the film will show alternate bands of light and dark lines. These lines can be accounted for only on the basis of constructive interference (reinforcement) and destructive interference of light waves. When the film is held vertically, some of the liquid falls to make the film wedge-shaped, which permits reflection of light from the front surface of the film and also from the inside of the back surface. (Refer to Figure 424.) There is thus the possibility of reflected waves from these two surfaces being "in step" or "out of step." For example, some of the incident rays will be reflected from the front surface as rays F_1, F_3, F_5, F_7, and so on. However, some of each ray will pass through to the rear surface, and rays F_2, F_4, F_6, F_8, and so on, will be reflected. (Refer to Figure 425.) The latter rays must travel a greater distance owing to the fact that they must traverse the liquid layer.[1] Thus, there is the possibility of constructive interference (reinforcement) and of destructive interference (darkness) when the rays from the front surface and the rear surface combine.

[1] If the separation of the two reflecting surfaces corresponds to one-fourth of a wave length so that the difference in the length of the paths is one-half of a wave length, one finds a dark line (destructive interference) resulting from the union of F_1 and F_2. At the point where the separation of the film surfaces amounts to $\frac{1}{2}\,l$, the union of the reflected waves F_3 and F_4 will result in constructive reinforcement (bright line). Actually, the full explanation for the alternate lines of interference and reinforcement also involves a change in phase for the wave reflected from the back surface, but this need not concern the beginner. The essential thing to note is the presence of places where destruction and reinforcement occur alternately.

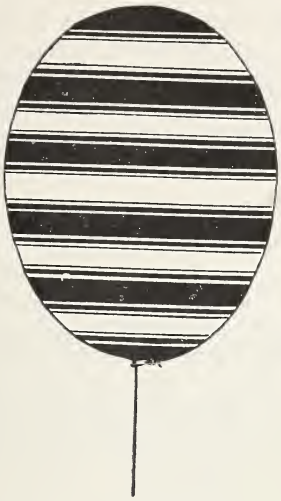

FIGURE 424. INTERFERENCE AND REINFORCEMENT OF LIGHT WITH A SOAP FILM

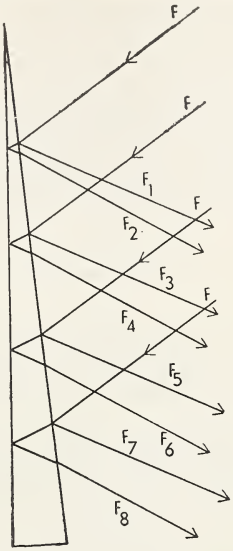

FIGURE 425. INTERFERENCE AND REINFORCEMENT OF LIGHT WITH THIN FILMS

Another common illustration of constructive and destructive interference with light can be seen in the splotches of oil dropped on a wet pavement. Close observation will reveal brightly colored alternate light and dark bands.

Thus, by the early part of the nineteenth century the facts concerning reflection, refraction, diffraction, reinforcement, and interference of light waves were clearly recognized and were accepted as conclusive evidence for the wave theory of light. Reference has already been made (page 784) to the significance of the measurements of the velocity of light in water as disproving the corpuscular theory. In a later chapter (Chapter 45), in connection with spectra, it will be shown that light also responds to the Doppler effect. To the scientific workers of the nineteenth century, there was not the slightest doubt that light was energy transmitted by a *transverse wave motion*. Newton's corpuscular theory was well-nigh forgotten.

The wave theory of light seemed to get on firmer and firmer ground with the passage of time, except for one disconcerting question: What is the medium for the propagation of light waves? The early backers of the wave theory were frank enough to say that they did not know what the medium was, but they felt sure that it would be merely a question of time until it

would be discovered. They were so sure that it would soon (*ca.* 1800) be found that they were bold enough to name it the *ether*, a substance that permeated all space. They thus inaugurated one of the famous hunts of science. Scientists the world over rushed into the search, each in the hope that he would be the fortunate scientific detective who would find the elusive *ether*. In the chapter dealing with wave motion (Chapter 40) it was shown that the various facts concerning any form of wave motion can be interpreted by the use of two relationships:

$$(1)\ v = fl, \quad \text{and} \quad (2)\ v \propto f \propto \sqrt{\frac{\text{Restoring force}}{\text{Inertia per unit volume}}}$$

The first relationship has been found to hold for light over an enormous range of frequencies. Attempts to apply the second equation to light, however, have led to an impasse. It was difficult for the early protagonists of the wave theory to account for a restoring force in any kind of medium that would account for the enormous frequencies and velocity of light. If the restoring force, for example, were something analogous to the property of elasticity — the tendency of matter to return to its original condition after being deformed by any process — the elasticity of the ether would have to be beyond the elasticity of the finest spring steel. At the same time, the density of the ether had to be comparable with that of the best vacuum. This, of course, represents the ultimate of incompatibilities. Michelson, who achieved fame by measuring the velocity of light with such precision, augmented his fame by his inability to find the ether. For this purpose he devised an instrument called the *interferometer*, one of the most ingenious and sensitive measuring instruments ever devised by man. It can, for example, measure changes in the wave length of light of one part in five million. With this instrument Michelson and a co-worker, Morley, hoped to prove the existence of the ether. The basis for their experiment was this: the hypothetical ether should pervade all of space, and consequently there should be motion of the earth relative to the ether, and it should be possible to detect this motion by the Doppler effect. After performing hundreds of experiments under all conceivable conditions, Michelson and Morley were forced to the conclusion that they had found no certain experimental evidence for the existence of the ether. This led to another disconcerting question: Could empty space alone serve as a propagating medium for light?

Light as Electromagnetic Waves

The solution of any great difficulty often requires a synthesis of knowledge from fields which apparently have little connection with each other. The similarity between the laws governing the measurement of the attrac-

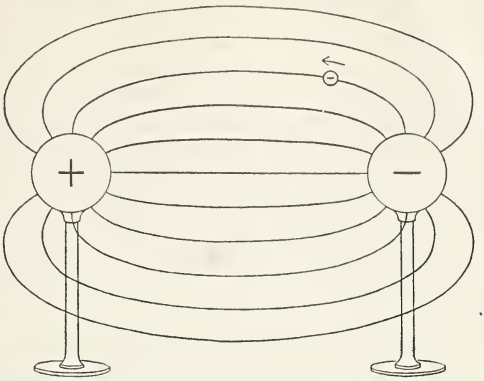

FIGURE 426. AN ELECTRIC FIELD CONSISTS OF LINES OF FORCE

tive force between two masses, between two unlike electric charges, and between magnetic poles of unlike sign has already been pointed out:

$$F \propto \frac{m_1 m_2}{d^2},\ F \propto \frac{p_1 p_2}{d^2},\ \text{and}\ F \propto \frac{q_1 q_2}{d^2}$$

The field about a magnet is something very real when it is investigated with a tiny exploratory magnet. (Refer to Figure 332.) If a unit north pole is placed anywhere in this magnetic field, it comes under an influence which causes it to move along a *line of force* to the south pole.

There is also a field of force between two unlike electric charges, such as diagramed in Figure 426. These lines of force are arbitrarily said to be directed from the plus to the minus charge. If an isolated negative charge is placed anywhere in this electric field, it travels along a line of force until it reaches the plus charge. The concept of a magnetic field of force and of an electric field of force composed of magnetic and electric lines of force was an important contribution of Faraday. Attention has already been called to the fact that these two kinds of fields always appear about a charge of electricity in motion. Thus, a change in the intensity of the current in the conductor shown in Figure 333 produces a simultaneous change in the magnetic field about the conductor. An electric current is explained as being merely electric charges in motion. Similarly, a change in a magnetic field simultaneously produces a change in an electric field in its neighborhood. You should recall also that the electric current and the magnetic field are at right angles to each other, as shown in Figure 333.

About 1860, Sir Clerk Maxwell discovered that the behavior of Faraday's lines of force could be expressed mathematically. This had a number of startling results. In the first place, a change in the intensity of a magnetic or electric field must spread throughout that field with a measurable

velocity. The electrons constituting the current in a sixty-cycle alternating current, for example, undergo one hundred and twenty reversals of directions of travel each second. This means that the magnetic field at right angles to the line must spread throughout the region and collapse sixty times each second. The field must therefore have an oscillating character. The equations of Maxwell indicated that electric fields and magnetic fields must coexist, and that the velocity of travel was 3×10^{10} cm/sec, which is also the *velocity of light.* Maxwell was forced to the conclusion that "there was no doubt that light itself is an electromagnetic phenomenon." The evidence, of course, is inferential, being based upon the belief that magnetic and electric lines of force spring into existence and collapse with the same velocity as light.

It is to be noted that the ether has been entirely discarded, and has been replaced by the concept of lines of force traveling through space with the velocity of light. Most of the work of Maxwell on the electromagnetic theory of light was done in the decade 1860 to 1870. The negative result of the Michelson-Morley experiment in 1887, then, merely served to substantiate the conception of Maxwell that light was an electromagnetic wave.

The Electromagnetic Spectrum

It is a simple matter to show that the wave length of visible light extends from about 7×10^{-5} cm for red light to about 4.1×10^{-5} cm for the visible violet light. The frequencies of these forms of light are:

For red light:
$$f = \frac{v}{l} = \frac{3 \times 10^{10} \text{ cm/sec}}{7 \times 10^{-5} \text{ cm}}$$
$$= 4.3 \times 10^{14} \text{ vibrations per second}$$

For violet light:
$$f = \frac{v}{l} = \frac{3 \times 10^{10} \text{ cm/sec}}{4.1 \times 10^{-5} \text{ cm}}$$
$$= 7.3 \times 10^{14} \text{ vibrations per second.}$$

The range of frequencies for visible light corresponds, then, to just about one octave.

There is nothing in the electromagnetic theory of light that restricts the vibrations of electromagnetic lines of force to this particular band of frequencies. A form of invisible light, the infra-red, had been discovered in the early part of the nineteenth century. We now know that infra-red rays are electromagnetic in character, with wave lengths as much as seven hundred times greater than those of visible red light. In fact, every warm flatiron or other hot object sends out invisible infra-red rays which, when intercepted by the body, produce warmth. The picnicker has found from experience that frankfurters are more quickly roasted over a bed of glowing red coals than over a high smoky flame. The glowing coals are a rich source of infra-red rays. Almost simultaneously with the discovery of the red rays there came the discovery of another form of "black light" — the

ultra-violet. This is a portion of the electromagnetic spectrum with wave lengths about one-third as great as the visible violet (4×10^{-5} cm). The sun and all objects at white heat send out ultra-violet rays, invisible to the eye, but resulting in definite physiological effects, such as sunburn and tanning of the skin. The hot rays of the summer sun are especially rich in the ultra-violet. The mercury arc lamp is another rich source.

Maxwell was quick to point out that there was no reason to doubt the existence of electromagnetic waves with wave lengths both longer and shorter than the infra-red and the ultra-violet. In 1887–88, Hertz in Germany experimentally proved that an oscillating electric charge sent out the waves we now call radio waves. Even our sixty-cycle alternating-current light circuits actually send out radio waves of a very great wave length. About the turn of the century, Marconi found practical application for these radio waves in wireless communication. In 1895, Roentgen discovered the mysterious penetrating rays that have ever since been referred to by the term Roentgen himself applied, namely, X-rays. Eventually these also were proved to be electromagnetic waves with wave lengths as short as 5×10^{-7} cm and frequencies as high as 6×10^{16} cycles per second. The tubes now used to produce X-rays still employ Roentgen's method of bombarding a metal target with a stream of fast-moving electrons. The improvements have been in the direction of increasing the number and the velocity or kinetic energy of the electrons which hit the target. In the modern Coolidge X-ray tube (refer to Figure 427), the electrons are obtained from a white-hot filament heated by electricity. At the same time a very high potential (150,000 volts) is applied across the filament and the tungsten target, which is made positive. This type of tube is a rich source of X-rays. The tube must be highly evacuated. X-rays possess so much energy that they penetrate many forms of matter opaque to visible light and thus can be used to find hidden defects in metal castings, to locate foreign objects in

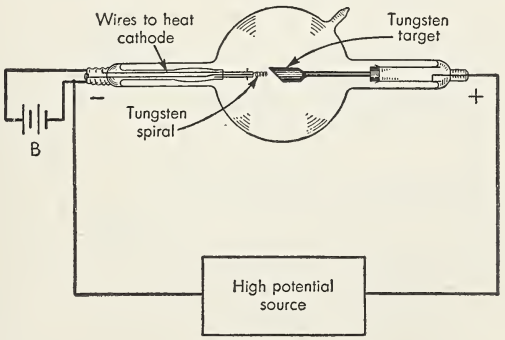

FIGURE 427. THE COOLIDGE X-RAY TUBE

the body, study breaks in bone structure, or locate diseased areas in the body, including, of course, the teeth.

The whole gamut of electromagnetic waves have certain common characteristics:

1. They are all produced by rapidly oscillating systems of an electrical nature (refer to Table 65).
2. They all travel with the velocity of light, 3×10^{10} cm/sec.

TABLE 65. ELECTROMAGNETIC SPECTRUM

(The values are approximate)

Name	Wave length	Frequency v.p.s.	Source	Method of Detection
60-cycle A.C. and other long electromagnetic	Thousands of Km	60	Electric Generator	Electromagnetic Induction
	2×10^{6} cm	1.5×10^{4}		
Wireless and radio			Oscillatory Electric Circuit	Electrical Resonance
	4×10^{3} cm	7.5×10^{6}		
Short Hertzian				
	3.5×10^{-2} cm	9×10^{11}		
Infra-red, or heat			Vibrating Molecules and Atoms	Thermopile or Bolometer
	7×10^{-5} cm	4.3×10^{14}		
Visible light				Eye or Photography or Fluorescence Effects
	4.1×10^{-5} cm	7.3×10^{14}		
Ultra-violet				
	1.2×10^{-6} cm	2.5×10^{16}	Vibrating Electrons in Atoms	
Extreme Ultra-violet				Photography Fluorescence
	5×10^{-7} cm	6×10^{16}		
X-rays				Photography or Radiation Potential
	1.2×10^{-9} cm	2.5×10^{19}		
Gamma rays			Atomic Explosion	Photography or Ionization
	5×10^{-11} cm	6×10^{20}		
Cosmic	1×10^{-12} cm	3×10^{22}	?	Geiger Counter and Wilson Cloud Chamber
	1×10^{-13} cm	3×10^{23}		

3. They all represent energy.

4. They all undergo reflection, refraction, diffraction, interference and reinforcement, and the Doppler effect.

Reference has been made several times to the enormous quantity of energy received from the sun. This energy is radiated from the sun largely as infra-red rays, visible light, and ultra-violet rays as transverse waves with a velocity of 3×10^{10} cm/sec. This type of energy is often called *radiant energy*. It does not become ordinary heat until it is absorbed on the earth.

The common vacuum bottle is effective in keeping liquids hot or cold primarily because it prevents the loss or entrance of radiant energy. The vacuum bottle itself is constructed with an inner and outer wall of thin glass. The inside of the inner and outer walls is then carefully silvered, after which the air between the two walls is evacuated with an efficient air pump and the bottle sealed to keep out the air. Such a vessel will keep liquids hot or cold for many hours. Transference of heat by conduction is made relatively small by the thin glass walls and the cork, which are very poor conductors of heat. Transference of heat through the double wall by convection is prevented by the vacuum. Loss of heat by radiation is made very small by the silver lining, which prevents the escape and entrance of infra-red rays by the process of reflection. Most of the heat loss is by radiation unless prevented by the silver lining. Infra-red rays can be intercepted and brought to a focus just as can visible light. Range-finders — which locate invisible war vessels or "see" bombing planes through clouds or in the dark — operate by intercepting and focusing the infra-red rays from firing guns or hot airplane engines.

Application of Electromagnetic Waves

It is worthy of note that most of these radiations now have many important applications. Only a few of their characteristics and uses can be mentioned.

1. *Radio waves.* These are produced by any rapidly oscillating electric current obtained with a specially designed vacuum tube. The dial on a radio set indicates that by *resonance* it is able to pick up waves with frequencies varying from 550 to 1500 kilocycles, which correspond to lengths of 547.5 to 200 meters from crest to crest.

2. *Infra-red.* These are ordinary heat waves, which are best absorbed by dark unpolished surfaces. Greenhouses are often heated in winter only by the infra-red rays from the sun which pass through the glass to be absorbed by the dark soil within the greenhouse. Every warm object radiates infra-red rays. Photographic film is now available which is sensitive to the infra-red, making photography possible even in the dark.

3. *Ultra-violet.* These rays are present in large amounts in sunlight and in the light from a mercury-vapor lamp. They have a great physiological

significance, for certain vitamins are formed in the human body when the skin is exposed directly to sunlight or ultra-violet light. One reason for a higher incidence of certain vitamin deficiency diseases in the winter time is the reduced possibility of bodily exposure to sunlight. It is unfortunate that ordinary window glass does not transmit the ultra-violet. Mercury-vapor lamps are enclosed in quartz, because this material readily transmits the ultra-violet.

4. *X-rays.* The manner of producing X-rays and some of their applications were mentioned on page 791. These rays are of great significance because they have made possible the determination of the atomic numbers of the elements by the method of Moseley (refer to page 466) as well as the crystal structure (crystal lattice) of solids and liquids.

5. *Cosmic rays.* This is the last addition to the family of electromagnetic waves. Cosmic rays are at once the most penetrating radiation known and the least understood. These rays strike the earth from outer space and carry so much energy that they will pass through many yards of lead. The nature and significance of these rays offer one of the very important unsolved problems of science today.

Thus far the similarities between the various electromagnetic waves have been emphasized. On the other hand, light waves show one striking dissimilarity, namely, the energy associated with the wave increases enormously as the wave-length decreases or the frequency increases. Visible light will not pass through many ordinary substances. The importance of X-rays lies in the fact that they penetrate many objects opaque to ordinary light, thus making X-ray photography possible. The gamma rays from radium will pass through inches of lead, and cosmic rays, which come from outer space, penetrate deep lakes and into deep mines. They represent the most concentrated form of energy thus far discovered. The relationship between the energy of the wave and its frequency is a very simple one, namely:

$$E(\text{nergy}) \propto f(\text{requency}), \text{ or}$$
$$E = \text{constant} \times f = hf.$$

The constant h is known as Planck's constant and has the numerical value 6.55×10^{-27} erg-seconds. This relationship makes it easy to compute the relative amounts of energy associated with various types of electromagnetic waves, as summarized in Table 66. Notice the large amount of energy associated with X-rays and gamma and cosmic rays as compared with light. One of the most interesting recent applications of high energy radio waves — radar — is a development of World War II. The widespread use of the airplane made it necessary to detect airplanes in the dark or in the clouds while still many miles from their objectives. Radio waves of extremely short wave lengths, about one centimeter, are used for this purpose. A wave length of one centimeter means a frequency of about

TABLE 66

Type of radiation	Mean value of frequency (f)	Energy in ergs (hf)	Energy relative to that of light
Radio waves	1×10^{6}	6.55×10^{-21}	2×10^{-9}
Infra-red	3×10^{13}	19.7×10^{-14}	5×10^{-2}
Visible light	6×10^{14}	39.3×10^{-13}	1
X-rays	3×10^{18}	2.0×10^{-8}	5×10^{3}
Gamma rays	3×10^{19}	2.0×10^{-7}	5×10^{4}
Cosmic rays	3×10^{22}	2.0×10^{-4}	5×10^{7}

3×10^{10} cycles, which is very much greater than the frequency of ordinary radio waves. These ultra-high-frequency radio signals are sent out by the detector stations. When the waves strike an airplane which may be fifty or more miles at sea, partial reflection occurs. Owing to its high energy content, the small part of the original signal which is reflected back to a detector station can be picked up and amplified. The reflected waves will be picked up by more than one detector station, and each station can determine the direction of the plane which reflected the waves. Using data obtained from more than one station, it is a simple task by triangulation to locate an approaching airplane. (Refer to page 43.) Airplane detector stations can detect the approach of enemy airplanes while they are still many miles away.

Light as Photons

Perhaps the reader is now ready to accept the theory that light consists of electromagnetic waves. Certainly there should be a secure foundation for a theory which was able to predict the existence of unknown waves, which could serve as a unifying principle for studying radio waves, the infra-red, visible light, ultra-violet, X-rays, and gamma rays, and which led to many important discoveries. But during the early part of the twentieth century certain facts were discovered concerning light which could be explained only by assuming that light consists of small particles having mass and definite amounts of energy. These particles came to be known as *quanta* or *photons*. The names of Einstein, Millikan, and Arthur Compton are associated with this modern version of Newton's corpuscular theory of light. In Chapter 35 there was a discussion of the photoelectric effect. The wave theory of light is unable to account for the ejection of electrons from a metal surface when illuminated. (Refer to Figure 328.)

According to the wave theory of light, energy travels from a candle, for example, throughout space in all directions, and only a small fraction of the total light impinges upon the metal surface in the photoelectric tube. The energy for causing the ejection of an electron from the metal surface according to the wave theory, then, would have to be accumulated by long exposure, and the rate of emission of electrons would be low. Experimentally,

there is no time lag whatever in the ejection of electrons. The only explanation possible is that the incident light consists of discrete particles which contain enough energy themselves to eject electrons. These discrete particles of light, or packets of energy, are called quanta or photons. The energy of these particles depends only upon the frequency of the incident light, not upon the intensity of the light, since $E = hf$. This may be put differently: according to the wave theory of light, the energy of a candle is distributed continuously in all directions in space. According to the modern corpuscular theory, the energy is sent out in the form of photons, each of which represents a package of energy which varies in magnitude with the frequency. Thus the light energy is distributed out in space in the form of very small bits of light, each of which represents a relatively large amount of energy.

The various theories concerning the nature of light, in and out of favor with successive generations, offer a good illustration of the need for flexibility and adaptability in the scientific point of view. Newton explained light as corpuscles; Huygens and Young, as waves traveling through the ether; Maxwell, as electromagnetic waves. Compton says light consists of photons, and now, to make the confusion still greater, though perhaps bringing us nearest to solving the mystery, two other Americans, Germer and Davisson, have shown that a stream of electrons (particles of definite mass) when shot through a thin layer of a crystalline substance undergo *diffraction*, a test for wave motion.

Brief reference was made in Chapter 3 to one of the outstanding recent developments in the field of optics, the perfection of the electron microscope. The ordinary microscope employs visible light and can be used only to examine objects relatively much larger than the wave length of light. This is due to the fact that the microscope reveals objects which cast sharp shadows. Thus, in Figure 428 the image is revealed by the light that passes by the object AB. Light rays passing the ends of the object AB must undergo bending or diffraction. When the length of AB is very short, the diffracted light originating at A and B will fuse in the same region at $A'B'$ to form an indistinct image. This effect and a number of other factors set a practicable limit of magnification of about two thousand for the best microscope with glass lenses. The amount of diffraction, of

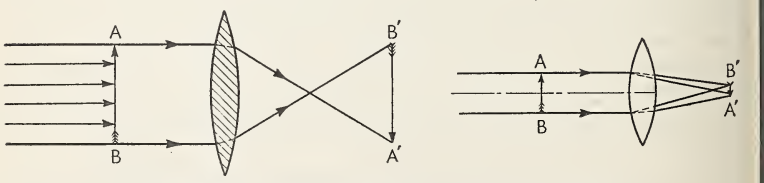

FIGURE 428. VERY SMALL IMAGES TEND TO BLUR

course, is a function of the wave length of the light; that is, as the wave length decreases, the amount of bending (diffraction) also decreases.

One function of scientific theories is to point the way to further advances. The discovery of Germer and Davisson, that streams of electrons behave as waves with wave lengths shorter than those of light, suggested the possibility of a microscope employing streams of electrons instead of visible light. Thus was born the idea of the electron microscope. Electrons are many times smaller than light waves and when traveling as waves have wave lengths considerably shorter than those of visible light. Thus, diffraction effects around the edges of an object are reduced to such an extent that magnifications as large as fifty thousand are possible in the electron microscope. Under this magnification an object with a diameter of one micron (10^{-4} cm) would appear to have a diameter of five centimeters. In an electron microscope the "light" consists of electrons from a heated filament given a high speed by the application of a high potential. The "lenses" for directing the path of the electrons are properly spaced and intense magnetic and electric fields. After traversing the objects and producing shadows, the electron waves are brought to a focus on a photographic plate. (Refer to Figures 18, 19, and 20.)

As for the question, What is light? — no one yet knows for a certainty. Experimentally, light seems to travel as transverse waves without a medium. When it is perceived by the eye, or falls on a photographic plate, or manifests itself in a photoelectric cell, it seems to consist of particles. Moreover, streams of particles, such as electrons and protons, exhibit the behavior of waves. Radiations of very short wave lengths, or of high frequencies, seem to consist predominantly of photons. The final answer to our question must await further experimentation and further testing of theories.

SUMMARY

1. Newton did not clearly recognize the phenomena of diffraction and interference in connection with light and therefore accepted a corpuscular theory of light which he thought adequately accounted for its reflection and refraction.
2. The final overthrow of Newton's corpuscular theory came during the middle of the nineteenth century, when, contrary to the prediction of Newton, light was found to travel slower in water than in air.
3. About 1800, Thomas Young and many others demonstrated that light can be diffracted and that light undergoes constructive and destructive interference. This led to the general adoption of the theory that light is a form of wave motion traveling upon a hypothetical medium called the ether.
4. Huygens' principle for light states that every point on an advancing wave front acts as a center for the production of other wave fronts.
5. The spreading of light into shadows in back of sharp edges beyond a small opening to produce various interference effects is called diffraction. Diffraction can be explained by Huygens' principle.

6. The theory of light as waves traveling on ether had to be abandoned because of an inability to get any objective evidence for the existence of the ether.
7. Maxwell originated the conception of light as electromagnetic waves. Around an oscillating electrical current there coexist magnetic and electrical fields at right angles to each other. These expand and collapse, setting up a series of waves which travel with the velocity of light. Visible light consists of electromagnetic waves sent out by oscillating electrons in substances emitting light with a frequency range of 4.3×10^{14} to 7.3×10^{14} v.p.s.
8. Radio waves, infra-red rays, ultra-violet rays, X-rays, gamma rays, and cosmic rays are forms of electromagnetic waves which differ from visible light in frequency and wave length and in their applications.
9. Electromagnetic waves have three common characteristics: (*a*) they are produced by rapidly oscillating systems electrical in nature, (*b*) they all travel with the velocity of light, and (*c*) they all undergo the various phenomena characteristic of wave motion — reflection, refraction, diffraction, interference and reinforcement, and the Doppler effect.
10. All the various forms of electromagnetic waves with the exception of cosmic rays have many important applications.
11. The energy associated with electromagnetic waves is directly proportional to the frequency.
12. During recent years, Einstein, Millikan, and Compton have shown that there are certain phenomena, such as the photoelectric effect, that cannot be explained by the electromagnetic theory of light, but that can be explained on the assumption that light consists of particles called photons.
13. Two Americans, Germer and Davisson, have shown that fast-moving electrons behave like waves in that they undergo diffraction.
14. At the present time there is no single comprehensive theory of light. Most light phenomena can be explained only by using the electromagnetic theory of light, but certain other phenomena, such as the photoelectric effect, can be explained only on the basis of photons or quanta of energy, and the whole problem must attempt also to reconcile the wave-like behavior of fast-moving electrons.

STUDY EXERCISES

1. At the right are listed the names of famous scientists who have contributed to our knowledge concerning light. Associate these names by number with the contributions given below:

.... Promulgated the electromagnetic theory of light.
.... Experimentally determined the present accepted value for the velocity of light.
.... First proved that a rapidly oscillating electric current sends out the waves predicted by Maxwell, which are now called radio waves.
.... First experimentally proved that light travels slower in water than in air, contrary to the prediction of Newton.

1. Newton
2. A. Compton
3. Huygens
4. Young
5. Michelson
6. Foucault
7. Hertz
8. Marconi
9. Maxwell

.... One of the first to get reliable observational evidence for the enormous velocity of light by making observations on one of the satellites of Jupiter.
.... Conceived the space about a charged body to be filled with lines of force.
.... The inventor who first utilized radio waves for purposes of communication.
.... The first investigator to write exhaustively on the subject of light.
.... Originated the theory that light is a wave motion traveling through the ether.
.... Presented experimental evidence which can be explained only by assuming that light consists of packets of energy called photons.
.... The inventor of the corpuscular concept of light.
.... First proved that it is possible to get interference and diffraction effects which demand that light travel in transverse waves.

10. Faraday
11. Roemer

2. Electromagnetic radiations have definite characteristics as to velocity, frequency, wave length, and energy content. Indicate by number (1 to 6) the order of change, if any, of these characteristics for the following kinds of radiation:

	Frequency Lowest = 1	Wave Length Longest = 1	Velocity	Energy Content Smallest = 1
Radio waves	.....	.....	.....	.....
Ultra-violet	.....	.....	.....	.....
X-rays	.....	.....	.....	.....
Infra-red	.....	.....	.....	.....
Gamma rays	.....	.....	.....	.....
Visible light	.....	.....	.....	.....

3. Below are listed certain experimental products which can be used to produce, detect, or utilize various kinds of radiations. Indicate by number which kind of radiation(s) is (are) involved in each.

.... Produced by a rapidly oscillating electric current.
.... An ordinary electric flatiron is a rich source of .....
.... Is present in direct sunlight and in the light from a mercury "sun lamp."
.... Produced by the impact of a rapid stream of electrons on a metal target in an evacuated tube of special design.
.... Are easily detected by the eye.
.... Will readily affect a photographic plate.
.... Readily penetrate many opaque materials, making photography of such materials possible.
.... Are used for danger signals because they are refracted less than other forms of visible light and more readily penetrate haze.
.... Originate in the disintegration of radioactive elements.
.... Responsible for sunburn.
.... Can be used to ionize air to operate a Geiger counter.

1. Radio waves
2. Ultra-violet
3. Infra-red
4. Gamma rays
5. X-rays
6. Visible red
7. Visible violet

.... Can be detected by "tuning" a second electric current to oscillate with the same frequency as the radiation itself.

.... Originate in the coals of a camp fire and can be used to roast frankfurters.

.... Can be used to make photographs in the dark.

4. A certain radio station operates on a frequency of 670 kilocycles. What is the wave length of its radio wave in meters? NOTE: Take $v = 3 \times 10^{10}$ cm/sec.

5. A certain radio station sends out a wave with a length of 517.5 meters. What is the frequency?

6. Below are listed various phenomena involving light. At the right are listed various attributes of light as a wave motion. Indicate by number which attribute best can be used to explain the various phenomena.

.... The light from a comet approaching the earth appears bluer than when it is receding from the earth.

.... The native Indian learned by experience that, if he was to spear a fish in water, it was necessary to aim below the apparent position of the fish in the water.

.... Thin films, such as a soap bubble, often reflect light as alternate dark and light bands which are colored.

.... A stick partly immersed in water appears bent.

.... A swimming pool ten feet in depth does not *appear* to be so deep when observed from above.

.... Trees at the margin of a pool can often be seen in the surface of the water.

.... The colors of the rainbow can often be seen when the sun strikes the water spray from a lawn sprinkler.

.... The light seen through a thin crack often appears to consist of alternate dark and light lines.

1. Reflection
2. Refraction
3. Diffraction
4. Doppler effect
5. Destructive interference
6. Constructive interference

FOR FURTHER READING

1. LOEB, L. B., and A. S. ADAMS, *The Development of Physical Thought.*
The whole problem of the nature and various aspects of the electromagnetic spectrum is discussed on pages 397–403, 418–432, 451–463, 582–597. Some of this discussion is highly technical, but there is much descriptive material that is not beyond the interests of the layman.

2. LEMON, H. B., *From Galileo to the Nuclear Age.*
The electromagnetic spectrum is discussed in Chapter 39. See also pages 370–371 and 402–409.

3. BRAGG, WILLIAM, *The Universe of Light.*
Chapters III and IV are concerned with color by interference and absorption. The electromagnetic spectrum and the experimental evidence for both the wave and corpuscular theories of light are presented in Chapters VII and IX.

45

Messages from the Stars: Spectra

MAN HAS ALWAYS BEEN INTERESTED in his environment. For primitive man the environment was a relatively small area in which he "lived and moved and had his being." But with the passage of time better methods of transportation and communication were gradually evolved with a gradual widening of the boundaries of the environment. With the advancement of science this progress has continued until the known boundaries of our environment are in astronomical space. Our solar system is but a small part of a huge assemblage of stars called a galaxy, the length of which is perhaps one hundred thousand light-years and the diameter about half that quantity. Furthermore, the astronomer knows that our galaxy is but one of many similar galactic systems throughout the universe. The interpretation of our universe involves many questions concerning distances, sizes, temperatures, and composition of heavenly bodies, much of which is known. It is a fair question to ask how the scientist obtained this information. There is only one answer: by a thorough understanding of light. For example, in an earlier chapter we learned that helium was first discovered in the sun in 1868 by Janssen and Lockyer while observing a total eclipse of the sun. A period of nearly thirty years elapsed before Ramsay in England found that helium exists on the earth. The achievement of Janssen and Lockyer was possible because of their ability to decode a message of light from the sun. Thus, events are continually happening throughout the universe which are announced on the earth by streams of radiant energy, if man will but intercept those waves and decode the messages. The instruments commonly used for this purpose are the camera, the telescope, and the spectroscope.

As we have seen before, Sir Isaac Newton was among the first to inquire seriously into the nature of light. The simple experiment of dispersing the light of the sun into the colors of the rainbow was first described by Newton. The experiment can be performed with any triangular glass prism. Newton used rays from the sun, but the same effect is obtained by light from any glowing solid. In Figure 429 light from the sun is made to pass through two slits in order to get light rays that are essentially parallel. This narrow beam of light is then made to pass through a prism.

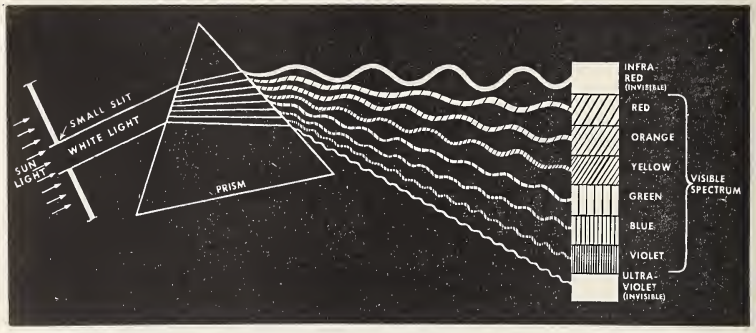

FIGURE 429. FORMATION OF A SPECTRUM BY REFRACTION OF WHITE LIGHT WITH A PRISM

The light emerges as a continuous band of color. Newton inferred correctly that white light is a fusion of the colors of the rainbow which suffer different degrees of refraction as they enter and leave the prism. Red light is refracted the least, and violet light is refracted the most. This continuous band of color is called a *continuous spectrum*. Newton confirmed his conclusion concerning the nature of white light by recombining colored light to form white light. (Refer to Figure 430.) Light from S forms a color spectrum as it emerges from prism A. This is revealed by placing a white screen S between the two prisms. This band of colors is then made to pass through prism B turned opposite to prism A, and the rays converge again as white light at D. White light, therefore, is a composite light consisting of all the colors of the visible spectrum — *red*, *orange*, *yellow*, *green*, *blue*, *indigo*, and *violet*.

A continuous spectrum is obtained if light from any glowing solid — white-hot carbon, red-hot iron, a glowing tungsten filament in a light bulb — or from an incandescent liquid, or from an incandescent gas under high pressure, is passed through a prism in a spectroscope. We now describe spectrum colors in terms of their frequency and wave length. (Refer to Figure 431.) Thus, blue light has a wave length of 45×10^{-6} cm and a fre-

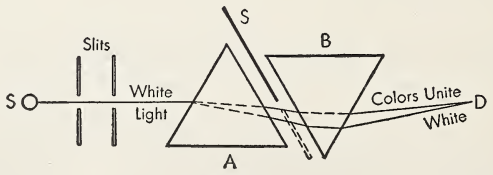

FIGURE 430
RECOMBINATION OF SPECTRUM COLORS TO FORM WHITE LIGHT

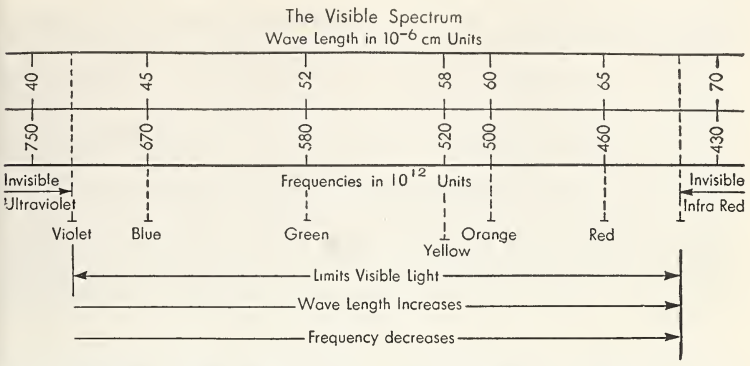

FIGURE 431. FREQUENCIES AND WAVE LENGTHS OF VISIBLE LIGHT

quency of 670 million million vibrations per second (670×10^{12} v.p.s.). The frequency of visible light is related to the wave length by the fundamental wave equation, $v = f\,l$. Hence,

$$f = \frac{v}{l} = \frac{3 \times 10^{10}\ \text{cm/sec}}{l}$$

Thus, blue light with a wave length of 45×10^{-6} cm has a frequency, f, or

$$f = \frac{3 \times 10^{10}\ \text{cm/sec}}{45 \times 10^{-6}\ \text{cm/vib}} = 670 \times 10^{12}\ \text{vib/sec.}$$

Carefully note that the borderline between the last visible red and the invisible infra-red is at a wave length of about 70×10^{-6} cm ($f = 430 \times 10^{12}$), and the borderline between the visible violet and the ultra-violet is at a wave length of a little more than 40×10^{-6} cm ($f = 750 \times 10^{12}$). These figures, which on first thought often seem fantastic, are based upon precise physical measurements.

The dispersive action of a prism on light is utilized in the spectroscope, one of the most important instruments used to decode the messages from the stars. (Refer to Figure 432.) At the left is any source of light. AB represents a metal tube with a narrow vertical slit at A and a common biconvex lens at B. The tube is adjustable for length so that the slit A can

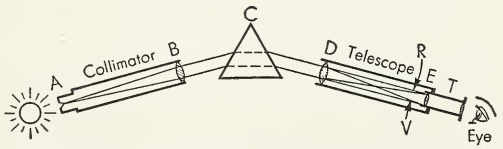

FIGURE 432. ESSENTIAL PARTS OF A SPECTROSCOPE

be placed at a distance from B corresponding to the focal length of lens B. On page 773 it was shown that parallel rays of light which pass through a bi-convex lens are made to converge at the principal focus. In the spectroscope, the reverse effect occurs; that is, diverging light rays from the slit are rendered parallel after passing through the lens B. These parallel light rays then undergo refraction in the prism C as in Newton's experiment. The refracted rays are then made to pass through another bi-convex lens D, which brings the light rays to a focus at the point E, where they may be observed with the eye or recorded on a photographic plate. The triangular prism C is usually made of glass or quartz. Glass readily transmits the visible spectrum but absorbs the ultra-violet. In order to transmit ultra-violet light, a quartz prism must therefore be used, since it is transparent to the ultra-violet. To study infra-red radiation, the prism must be made of common salt — sodium chloride. If one looks down the length of the tube AB with the lens B and the prism C removed, the eye will see a single line — the illuminated slit A. When the eye looks into T — the prism and lens having been replaced — *many* lines will be seen. These lines are images of the slit in different colors. For example, red light from the source will form a slit image (line) at R, and blue light from the source will form a line at V, since it is refracted to a much greater extent. Thus, each separate color in light from the source will be revealed by a different so-called *spectral line* when viewed at T. In connection with the use of the spectroscope, it is worthy of note that the eye is a very imperfect device for studying the spectrum, since it readily tires and is not sensitive to either the infra-red or the ultra-violet. The light-sensitive silver halide (emulsion) of the modern photographic plate is sensitive to both the infra-red and the ultra-violet as well as the visible spectrum. Furthermore, the effects are accumulative and are recorded permanently. That is, spectra which cannot be seen are often photographed simply by prolonging the exposure. It is customary, therefore, to photograph spectra for a permanent record.

Kinds of Spectra

Continuous Spectra. We have said that all materials at high temperatures, whether incandescent solids, liquids, or compressed gases, emit a continuous spectrum similar to that of the sun. This is believed to be due to the rapid oscillation of electrons within the body and does not depend upon the nature of the substance heated. In the previous chapter, we learned that any oscillating electrical system emits electromagnetic radiation. The only differences are in the relative amounts of colored light which are present, and these are definitely related to the temperature of the body emitting the spectrum. Thus, a piece of hot iron not quite visibly glowing gives off its maximum radiation in the region of the infra-red. When visibly red-hot, there is an abundance of radiation in the visible red. At white heat, the shorter wave lengths — green and blue — are increased

in quantity, thus giving the total white effect. At the most intense temperature, found in some stars, blue radiation and even the ultra-violet predominate. The spectrum of a star thus reveals its temperature.

We have seen many times that the methodology of the physical sciences includes stating the relationship between two or more variable quantities in the precise symbolism of mathematics. The relation between the temperature of a hot body, such as a star, and the energy radiated, and the frequency of the radiation, is expressed in two very concise statements, the laws of Stefan and Wien. Stefan's Law states that the total radiation (energy) emitted is directly proportional to the absolute temperature of the body raised to the fourth power, or

$$E \propto T^4.$$

This means that if the temperature of a radiator is *doubled*, the rate at which it is sending forth energy is increased *sixteen* times.

The frequency of the radiation emitted by a hot body varies over a considerable range, but for every temperature there is a region where a maximum amount of energy is emitted. Wien's Law states that the frequency of the maximum radiation emitted varies directly as the absolute temperature, or

$$f_{maximum} \propto T \text{ or}$$
$$f_{maximum} = kT = 1.04 \times 10^{11}\ T.$$

The laws of Stefan and Wien are of importance because they provide methods for the determination of the temperature of bodies in space. Thus, experimentally, it is found that the frequency of the light of maximum intensity from the outer surface of the sun is $f = 6.2 \times 10^{14}$. Accordingly, Wien's Law indicates the surface temperature of the sun to be

$$T = \frac{6.2 \times 10^{14}}{1.04 \times 10^{11}}$$

or about 6000° A. or 5700° C.

Bright-Line Spectra. Incandescent gases at low pressures, if not highly ionized, give a spectrum consisting of fine colored lines instead of a continuous band of color. These line patterns are called *bright-line spectra.* (Refer to Figure 433.) Suppose, for example, common salt — sodium chloride — is vaporized in a hot flame in front of the vertical slit. The slit observed with the eye at T reveals *two* yellow slits very close together. These are called the *double spectral lines* of sodium in the yellow part of the spectrum. (Refer to Figure 433.) If light from glowing hydrogen is used to illuminate the slit, the eye at T (Figure 432) will observe four images of the slit — one red, one blue, and two in the violet part of the spectrum. These are the four prominent spectral lines of hydrogen. (Refer to Figure 433.)

For reasons given above it is now customary to record bright-line spectra on photographic plates. The spectral patterns of no two elements are ever

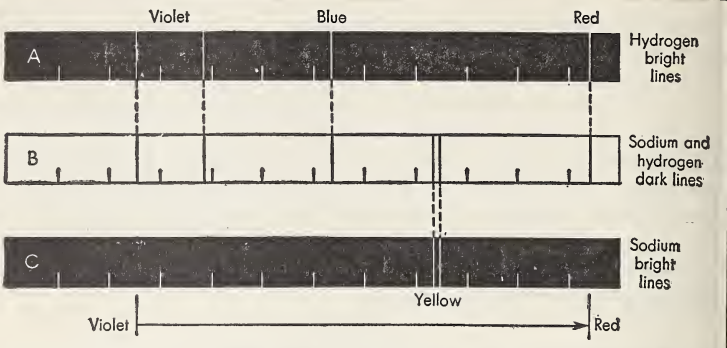

FIGURE 433. RELATION BETWEEN BRIGHT-LINE AND DARK-LINE SPECTRA

the same; they differ in the *number*, *location*, and *intensity* of the lines on the photographic plate. The line spectra of sodium and hydrogen are relatively simple. The spectrum of neon, on the other hand, consists of about eighteen lines in the red, two in the yellow, and about nine in the green-blue end of the spectrum; and the spectrum of iron vapor consists literally of thousands of lines.

The scientist has found the spectroscope an indispensable instrument for studying the composition of matter, whether in the laboratory or in a star when ordinary chemical methods of analysis fail. It was the spectroscope that made it possible for Janssen and Lockyer in 1868 to discover helium in the sun. Later, when Ramsay found helium in the earth, he proved that it was the element first found in the sun by showing that the spectral patterns were identical. The chemist has found the spectroscope an indispensable instrument for studying matter both on the earth and in space. Helium, argon, neon, krypton, rubidium, and cesium are but a few of the elements that were discovered by the use of the spectroscope.

Dark-Line Spectra. In the early part of the nineteenth century Fraunhofer, a Bavarian scientist, observed that a careful inspection of the continuous spectrum of the sun revealed many dark lines. These lines have ever since been referred to as *Fraunhofer lines*. Fifty years later, Kirchhoff another German scientist, observed that the positions of the dark lines coincided exactly with those of a bright-line spectrum. (Refer to Figure 433.) The explanation was soon found. Any gaseous body under low pressure and at high temperature, as in a star, sends forth a bright-line spectrum. The outer gaseous envelope of the star is at a lower temperature, and this cooler vapor absorbs the particular frequencies of colored light — the cause of the spectral lines — which are emitted by the same gas at a higher temperature. Thus, the dark and bright lines must coincide in bright- and dark-line spectra. Since the bright lines disappear because of

absorption in the cooler outer vapor, dark-line spectra are also called *absorption spectra.*

Most of the spectrographs obtained from various heavenly bodies are dark-line spectra which are checked against bright-line spectra from sources here on the earth. For example, if an astronomer wishes to determine the presence or absence of calcium in a certain star, with the aid of a spectroscope he will photograph the light from the star. Then, on the same photographic plate, he will photograph the spectrum emitted by a calcium compound volatilized in the laboratory. If the two sets of spectral lines coincide when one photograph is placed above the other, then calcium must be present in the star being studied. With the spectroscope, astrophysicists have been able to prove that over sixty of the elements known on the earth also exist in the sun.

The spectroscope is also used to determine the motions of heavenly bodies. In an earlier chapter we studied the Doppler effect (refer to page 738). If a body emitting any form of wave motion is approaching the observer, there is an apparent decrease in the wave length. We have seen that light is a wave motion. Therefore, when a source of light is approaching the observer, the wave length apparently decreases, and if the source of light recedes, there is an apparent increase in the wave length. As shown by a spectral photograph, this means that there is a shift in the position of the spectral lines — a shift toward the red end of the spectrum if the light source is receding, or a shift toward the violet end of the spectrum if the light source is approaching the earth, for red light has a longer wave length than violet light. (Refer to Figure 434.) The bright-line spectrum at the top and bottom is the reference spectrum from a laboratory source, in this case, sodium. The dark-line spectrum in the middle is from a comet and definitely proves that sodium lines are present. The slight shift in the position of the lines is also noticeable — in this case, a shift toward the red end of the spectrum. This indicates that there is relative motion which results in an increase in the wave length of the light, and either that the comet was receding from the earth or that the earth was receding from the comet. Which of these alternatives is the true explanation of the shift must be settled by interpreting other observational data. In the same

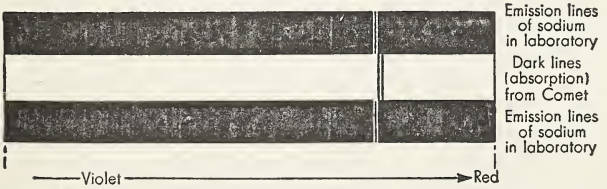

FIGURE 434. THE DOPPLER EFFECT DUE TO MOTION OF LIGHT SOURCE

way, it is easy to prove that the sun is rotating. All that need be done is t take spectrographs of light from opposite sides of the sun. From one sid of the sun the spectral lines are shifted toward the violet, while from th other the lines are shifted toward the red. This, of course, proves that on side of the sun is moving earthward, while the other side is moving awa from the earth. This means rotation of the sun. It is possible by measur ing the degree of shift of the lines to compute the actual velocity of ap proach or recession.

Composition of the Sun

Our knowledge of the chemical composition of the sun is due entirely t the spectroscope. The spectra of about eighty of the known elements o the earth are definitely known. Upwards of sixty of these elements ar certainly present in the sun. Hydrogen, helium, and oxygen exist in rela tively enormous quantities. The American astronomer, Henry Norri Russell, estimates that nearly half of the sun by weight is hydrogen. Ap proximately a fourth of the mass of the sun is due to oxygen, and heliu and certain metals account for about one-sixteenth and one-fourth of th mass, respectively. In the sun, only the elements carbon, boron, an nitrogen are in the form of compounds. Free electrons exist there in larg amounts. It is the presence of large quantities of hydrogen and electron that lead scientists to believe that protons — atoms of hydrogen whic have lost one electron — and electrons are converted into helium and th heavier elements as the hot gaseous body cools with a liberation of energy (See discussion below.) The metals that are definitely known to exist i appreciable quantities in the sun in order of abundance are: magnesium iron, silicon, sodium, potassium, calcium, aluminum, nickel, manganese chromium, cobalt, titanium, copper, vanadium, and zinc.

Source of the Energy of the Sun

Our dependence upon the sun for most of our energy has been repeatedl emphasized. The amount of the energy emitted by the sun is inadequatel described by the word enormous. The laws of Stefan and Wien can b applied to compute that the sun pours energy equivalent to 62,000 kil watts from each square meter. Knowing that the diameter of the sun i 864,000 miles, we can easily calculate that the energy radiated from th sun's entire surface is equivalent to about 0.4×10^{18} kilowatts. This i turn is equivalent to the combustion of 1.5×10^{10} tons per second of high grade coal. The magnitude of this quantity can be appreciated when yo realize that this is a hundred times larger than the annual production o coal in this country. Most of the energy radiated by the sun of course i lost in astronomical space. At right angles to the rays of light from th sun, heat is received at the surface of the earth at the rate of 1.98 calorie per minute on each square centimeter. This quantity is often called th

solar constant, and it is not sensibly changing with time. This is a power flow of about 3,700,000 kilowatts per square mile, and it is the energy that evaporates the water in the oceans, makes the coal deposits, heats the earth's surface, causes weather, and makes possible the growth of plant life — the important process of photosynthesis. It has been the dream of many scientists and engineers to tap this inexhaustible source of energy. But this still remains only a hope for the future.

The currently accepted theory, that of Bethe, for the energy of the sun, is a product of the last decade and has been discussed on pages 500–501. Nearly half the sun is hydrogen and this is slowly being converted into stable helium with a *loss in mass*, which becomes heat and radiant energy. Matter is being converted into energy in amounts far beyond that obtained by ordinary processes of combustion. Thus the combustion of four grams of hydrogen to produce water liberates about 136,000 calories,

$$2\,H_2 + O_2 \longrightarrow 2\,H_2O + 136{,}000 \text{ calories.}$$

But the conversion of a like amount of hydrogen into helium as it occurs in stars like the sun means a loss in mass,

$$4\,{}_1^1H \longrightarrow {}_2^4He + 0.032 \text{ grams as energy,}$$

$$4\,(1.008)\text{ g} \quad 4.002\text{ g}$$

This amount of mass appears as energy according to the Einstein equation,

$$\text{E(nergy)} = \text{m(lost)} \times 9 \times 10^{20}\,\frac{\text{cm}^2}{\text{sec}^2}$$
$$= \text{m} \times 9 \times 10^{20} \text{ ergs.}$$

This means that when one gram of hydrogen disappears in the sun there appear 9×10^{20} ergs of energy, which are equivalent to about 2×10^{13} calories, or three thousand tons of coal. The energy emitted by the sun means a loss of about four million tons of matter each second. But the amount of hydrogen for conversion into helium in the sun is so enormous that it will continue in its present state some 30 billion years longer.

Evolution of Stars

Stars apparently have a period of infancy, pass to maturity, and eventually die with a span of life that lasts billions of years. This conclusion is based upon the study of stars from the standpoint of size, surface temperature, luminosity, and composition. From the standpoint of size, stars can be conveniently divided into three groups: (*a*) giant red stars, (*b*) stars about the size of our sun, and (*c*) stars very much smaller than our sun, or dwarfs, which are also red stars. Antares is a typical giant red star. It is so large that it would fill our solar system out beyond Mars. Although it occupies a volume ninety million times greater than the sun, it has a mass

only forty to fifty times as great. Hence it is a very tenuous star. Th characteristic red color is due to its relatively low surface temperature – 3000° C. Antares is best seen in the southern sky during summer, when i can be found in the zodiacal constellation of Scorpius. Betelgeuse, in th upper east corner of the constellation Orion in the southern winter sky, i another example of a giant red star. These giant red stars are not ver numerous, and how they originate is not understood. One theory state that they originate as tenuous material thrown off by rotating nebulae. A a result of loss of energy by radiation, the star continues to shrink in vol ume. Furthermore, the gravitational pull between the relatively dens center and the outer reaches of the star also causes it to shrink. Thi shrinkage must cause an increase in the temperature of the star.

When a giant red star has contracted to a volume comparable to our sun it becomes a blue-white, or yellow star. This is its period of maturity It is significant that stars of the size of the sun are never red. Sirius, th brightest object in the evening sky with the exception of Venus and th moon, is a typical mature star. It can be seen in the winter sky in th southeast. Sirius has a surface temperature of 11,000° C. and radiate blue-white light. Sirius, in reality, is a double star having a companio which is a white dwarf. The companion star is only one-thirtieth as large but with a mass one-third as great as the more visible part of Sirius. Thi means that the density of the smaller star is ten thousand times that o water. Fifty cubic inches of this star's material would weigh more tha a ton. Matter of such extraordinary density is believed to consist o "stripped atoms" — atoms which consist only of the nuclei of the atom as a result of losing all the planetary electrons by ionization. Recall tha in Chapter 26 it was pointed out that most of the mass of an atom is du to the protons and neutrons in the nucleus.

The spectra of all mature (sunlike) stars reveal the presence of larg amounts of hydrogen and helium and many of the lighter metals, such a iron, calcium, and magnesium. The hydrogen is important, as it is th source of energy of the sun as postulated by Bethe. This stage persists a long as there is enough hydrogen in the star to continue forming helium As a mature star loses matter in the form of energy, it progressively get smaller in size and lower in temperature. There is a regular change i color from blue-white to white to yellow and even orange. As the sta approaches old age, it again becomes a red star — but now a red dwarf The red dwarfs are smaller, cooler, and fainter than the sun. Many o these stars are actually smaller than the earth and have temperatures con siderably lower than those that prevail on the sun. When a star reache the dwarf red stage it continues to shrink and cool, but only by direc radiation of energy, since the temperature is below that which will permi the conversion of hydrogen into helium and heavier elements. The deat of a star occurs when it ceases to be luminous. However, the events o

'star death" will always be entirely speculative, since the star can no onger send forth light to be intercepted for decoding by the telescopes and pectroscopes in the astronomical observatories.

Our own sun can be considered a "young mature" star. It has a surface emperature of approximately 6000° C. and is a typical yellow star. But in ll probability it is slowly approaching a white, or blue-white stage, like hat of Sirius. There is still a large amount of hydrogen present for con- ersion into helium and energy. This means that life on the earth will not ventually perish because of "cold death," but because of "heat death." f our sun becomes a star like Sirius, the amount of radiation will be so normously increased that all forms of plant and animal life on the earth ust perish. However, this should not be of any immediate concern to any f us, because this hypothetical event is still thirty billion years in the ture. The earth itself has been in existence only a matter of three illion years.

osmogony

Since the time of Newton, man has accepted the idea of a universe as vast but orderly and harmonious system undergoing changes in accord- nce with natural laws. The study of the origin of the cosmos, the size nd the changes occurring therein, is the science of *cosmogony* (see Chapter 7). The description of the heavens by the Psalmist is beautiful in its mplicity, "The heavens declare the glory of God; and the firmament oweth His handiwork." But the firmament is no longer conceived as e inside of a spherical surface which serves as a support for the stars, but space transcending the imagination of man.

alaxies and Nebulae

Even a very casual inspection of the evening sky indicates that the stars e apparently not uniformly distributed in space. The great band around e sky called the Milky Way contains a much greater apparent concen- ation of stars than in a direction perpendicular to the plane of the Milky ay merely because we are looking along the plane of a huge saucer- aped aggregate of stars, our galaxy. (Refer to Figure 435.) The sun nd solar system are but a small part of this galaxy, somewhat removed om its center. The disk of our galaxy has a diameter which may be as rge as one hundred thousand light-years and a thickness of ten thousand twenty thousand light-years. We, of course, are forever precluded from e possibility of seeing it from the outside. However, it is reasonable to lieve that if we could transport ourselves outside our galaxy, it would ve the appearance of certain *extra-galactic nebulae* which are common roughout astronomical space. These are in reality other disclike assem- ages of stars and suns. For example, in the constellation of Andromeda ere can be seen a small diffuse patch of light, the Great Spiral Nebula of

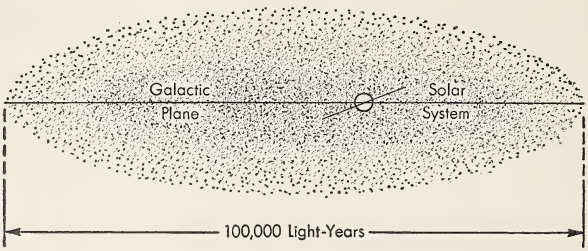

FIGURE 435. PLACE OF SOLAR SYSTEM IN OUR GALAXY

Andromeda, which is just discernible to the naked eye. (Refer to Figures 436 and 437.) It is a galaxy comparable to our own, consisting of many millions of stars extending through space for thirty thousand light-years and is perhaps ten thousand light-years thick. It is located nine hundred thousand light-years away from our solar system. There is evidence that this island universe in space is in rotation as is our own galaxy. Large numbers of these galactic systems are known to exist.

How far does the universe reach? The Rockefeller Foundation has donated six million dollars to build a telescope with a mirror lens 200 inches in diameter. This telescope, the mirror of which is twice as large as any that has been constructed up to this time, is to be housed in an

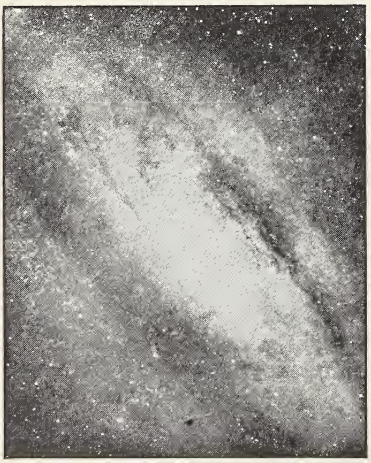

FIGURE 436. THE GREAT NEBULA 1931 IN ANDROMEDA
(*Courtesy of Mount Wilson Observatory*)

FIGURE 437. A NEBULA IN ANDROMEDA SEEN EDGEWISE
(*Courtesy of Mount Wilson Observatory*)

observatory on Mount Palomar in Southern California. It will penetrate four times farther into space than has been possible up to this time. A momentous question: What will this new telescope reveal concerning space beyond a million light-years? Surely science has come a long way from the concept of the Psalmist of the Old Testament!

SUMMARY

1. White light from a glowing solid or liquid or a gas under pressure can be dispersed by means of a triangular prism into a continuous spectrum, and this can be observed and studied with the aid of the spectroscope.
2. The spectrum colors differ in frequency and wave length. The wave length of light decreases and the frequency increases in going from red to violet light.
3. Incandescent gases at low pressures, if not highly ionized, produce a bright-line spectrum.
4. A dark-line spectrum rather than a continuous spectrum is obtained when white light passes through a relatively cool gas. In the sun's spectrum, these dark lines are called Fraunhofer lines.
5. The spectral patterns of elements differ in the number, location, and intensity of the spectral lines.
6. The spectroscope can be used to determine what elements are present in a substance of unknown composition.
7. The spectroscope can also be used to determine whether a body in space is approaching or receding from the earth because of the Doppler effect. A shift in spectral lines toward the red end of the spectrum means an increase in wave length and a recession of the light-emitting body from the earth, and a shift toward the violet means the opposite.
8. The relative amount of colored light received from a star depends upon its temperature. Stars at relatively low temperatures emit large amounts of the infra-red and red light, and stars at very high temperatures emit large amounts of violet and ultra-violet light.
9. The temperature of stars can be determined by applying Stefan's Law and Wien's Law.

   Stefan's Law: The total energy loss from a hot body by radiation is directly proportional to absolute temperature raised to the fourth power, $E = kT^4$.

   Wien's Law: For a radiating body, the frequency of the radiation corresponding to maximum loss of energy is directly proportional to the absolute temperature, or f maximum $= kT = 1.04 \times 10^{11}\ T$.
10. The sequence in the life of stars is believed to be (1) giant red stage, (2) blue-white to yellow stage, and (3) dwarf red stage.
11. Most of the energy radiated by our sun and by blue-white, white, and yellow stars is the result of annihilation of matter by conversion into energy.
12. Our sun, solar system, and the stars of our universe are part of a disclike

assemblage of stars perhaps 100,000 light-years in diameter and 10,000 t 20,000 light-years thick, called our galaxy.

13. The outer universe consists of many extra-galactic systems, which are ga axies similar to our own.

STUDY EXERCISES

1. Cross out incorrect phrases: Red light travels (faster than) (slower than (the same speed as) blue light and is refracted (more than) (less than) (th same amount as) blue light.
2. The sun observed near the horizon appears red. How can this be accounte for?
3. Green traffic signals are often more difficult to see than the red traffic signals especially during foggy weather. How can this be accounted for?
4. Indicate by checking in the appropriate column the type of spectrum tha would be observed in the following experiments:

	Continuous	Bright-line	Dark-line (absorption)
(*a*) The filament of an electric light bulb is observed through a spectroscope.			
(*b*) The light from a neon-light sign.			
(*c*) Copper vaporized in an electric arc.			
(*d*) The light from a distant star.			
(*e*) The light from a fluorescent lamp.			
(*f*) Sunlight observed through a solution of chlorophyll.			

5. Below are listed various types of information that astronomers collect con cerning various astronomical objects. Indicate whether or not this informa tion is obtained directly by the use of a spectroscope.

Yes No

.... The temperature of a star.
.... The mass of a star.
.... The elements present in (composition of) a star.
.... The age of the moon.
.... Whether the object is approaching or receding from the earth.
.... The distance to a star.
.... Whether or not there is life on Mars.
.... That certain stars which appear single to the eye consist of tw separate stars rotating about a common center.

FOR FURTHER READING

1. Lemon, H. B., *From Galileo to the Nuclear Age.*
Chapter 40 is recommended.
2. Bartky, W., *Highlights of Astronomy.*
Chapter 7 contains interesting speculations concerning the sidereal univers based in part on spectroscopic data. The theory that perhaps our universe expanding is included.

3. JEANS, J. H., *The Universe Around Us.*

Chapter IV deals with present ideas concerning the origin and history of stars — based largely on data recorded photographically with the aid of telescopes and spectroscopes. The spectroscope and spectrum analysis are discussed on pages 32–37 and 83–87. Excellent photographs of spectra.

4. FISHER, CLYDE, and MARIAN LOCKWOOD, *Astronomy.* New York: John Wiley and Sons, 1940.

The important instruments used in astronomy, including the spectroscope, are discussed in Chapter VI. There is a brief discussion of the different kinds of spectra.

5. CAMPBELL, LEON, and LUIGI JACCHIA, *The Story of Variable Stars.* Philadelphia: The Blakiston Company, 1941.

The story of pulsating stars is presented in Chapter 4. This little book is devoted to the subject of variable stars.

6. LUCKIESH, MATTHEW, and FRANK K. MOSS, *The Science of Seeing.* New York: D. Van Nostrand Company, 1937.

The senior author is an outstanding authority on the science of seeing. Chapter XI discusses thoroughly the objective and subjective aspects of color. The general reader will find this a very profitable chapter. Chapter XII is concerned with reading as a task.

46

The World We See

IN THE PRECEDING CHAPTERS it was shown that light is energy travelin through space in the form of electromagnetic waves or in streams photons exhibiting the characteristics of wave motion. The source of ligh may be a gas flame, an electric light globe, the sun, or a distant star, bu the general characteristics of this form of energy are the same. It travel irrespective of source, with the same incredible speed (186,000 mi/sec), speed which the human mind finds difficult to comprehend; it may travel i any direction and may be reflected, refracted, or diffracted. The comple ity of the matter is increased when it is remembered that there are man different wave lengths of light; the distance from crest to crest may be hun dreds of miles, as in radio waves, or but a millionth of a centimeter, a in X-rays. The different wave lengths correspond to different kinds light. The word "light" in ordinary usage refers to visible light, but i scientific language it includes also those types of light waves which are no detected by the human eye.

Most people think of "visible light" as designating the sensation pro duced by sunlight or by the light from an electric bulb or a lamp. It wa shown in the preceding chapter, however, that white light can be resolve into different colors. In the present chapter we shall be concerned wit the entire visible part of the spectrum and the various colors which com pose white light; for visible light is not only white light, but also the gree light from the fields, the blue haze in the sky, the many red hues from th setting sun, and the countless other colors which the human eye is able t discern. It is through color and form that we differentiate most of th objects in the world. The world we see is a world full of colors, for colo is *the interaction of light and matter.*

Analysis of a Sunbeam

It was shown on page 802 that when white light passes through a gla prism it is separated into different colors. White light, therefore, was ex plained as a composite of all the different colors of the visible spectrum – red, orange, yellow, green, blue, indigo, and violet. These different colo

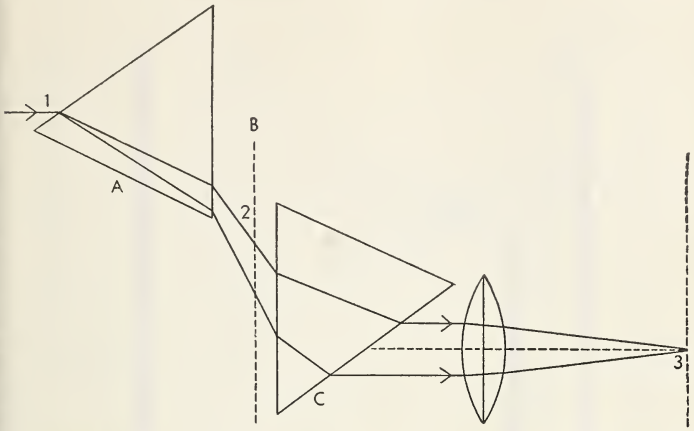

FIGURE 438. ANALYSIS OF WHITE LIGHT INTO THE COLORS OF THE CONTINUOUS SPECTRUM AND THEIR RECOMBINATION

rrespond to different wave lengths, which, as they pass through the glass ism, are bent or refracted to a different degree. Violet, which has the allest wave length, is bent the most, and red, which has the longest ave length, is bent the least. The other colors fall between these two tremes, one color merging into the other.

In order to show that the separation of a sunbeam into the different lors does not produce any essential change in the white light, the follow- g experiment was described. A beam of white light is allowed to pass rough the prism *A* at point (1) (Figure 438), and, when it emerges at (2), is separated into the continuous spectrum made up of the various colors, can be shown by inserting a white screen at point (2) as indicated by the tted line *B*. If this separated band of colors is now allowed to pass rough the second prism *C* turned oppositely to prism *A*, then the colors combine again and emerge at point (3) as white light.

osorption of Light and Color

Now, if white light is composed of several colors which correspond to finite vibration frequencies, then a *pure color* is one which is produced waves that have but one frequency; and such light is called *mono- romatic* light. But the colors of the world we see, the green color of the aves, the red color of the roses, and all the other colors that we see about are not pure, but are usually mixtures of two or more pure colors.

In order to understand why certain objects appear to us blue and others llow, it is necessary to consider the interaction between the object and e light which illuminates the object; with the exception of the sun and

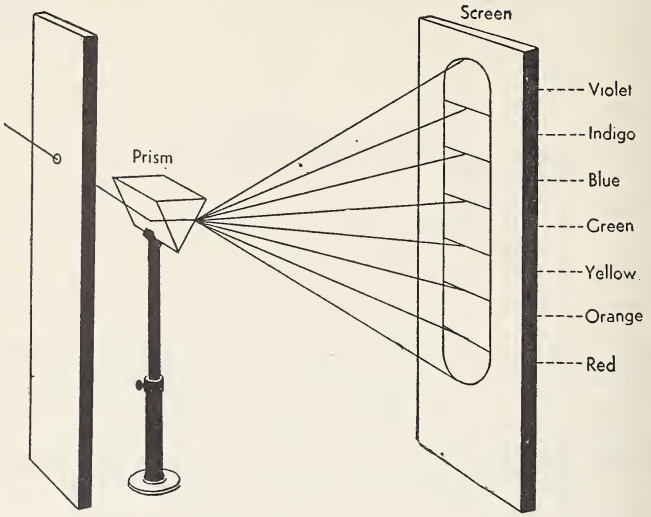

FIGURE 439. WHITE LIGHT PASSING THROUGH A PRISM IS SEPARATED INTO ITS COMPONENT COLORS

Red objects appear red when held in the red end of the spectrum on the screen and black in any other color.

the few objects which emit light, such as the electric light globe and burn ing substances, we see objects by means of reflected and transmitted light If we look through a window, the light from the outside is transmitte through the glass; if we look at a tree, a streetcar, or a dog, we see thes objects by means of light from some other source which first falls upo these objects and then is reflected to our eyes. Therefore, we can divid objects into *transparent* and *opaque*. It is clear that light does not g through opaque objects and, further, that most things which we see belon to this class. It will be advisable, therefore, to consider the color c opaque objects first.

If white light falls upon a piece of cloth that is opaque, and the clot appears white to our eyes, it is obvious that the white cloth has the prop erty of reflecting equally all colors. If the cloth appears red to our eyes, w can draw the tentative conclusion that the red cloth absorbs all the othe colors and reflects only those wave lengths which correspond to the re bands of the spectrum. To test our hypothesis, we can make use of th apparatus shown in Figure 439. White light passing through the pris is separated into its component colors, which are visible on the screen as continuous band. A small piece of cloth which appears red in daylig when held in the red end of the spectrum on the screen, appears red; whe

it is held in any other color, it appears black; therefore, the red pigment in the cloth absorbs the yellow, the blue, and other colors, and, since it does not reflect any light, it appears black. In the same manner a blue piece of cloth when held in the red end of the spectrum appears black, and gives the blue color only when held in the blue part of the spectrum. The plausible conclusion, therefore, is drawn that colored opaque objects appear red or yellow or blue because they have the power to absorb all the other colors, but reflect the red, the yellow, or the blue color, respectively. The absorbed light is changed into heat; this can be demonstrated by wrapping the bulb of one thermometer with a white cloth and that of another with a black cloth and exposing them to a uniform illumination from a source of white light. The white cloth reflects all colors; the black cloth absorbs all colors and changes the light energy to heat. The temperature in the thermometer whose bulb is covered with a black cloth rises more rapidly. Experience with wearing white and dark garments in the summer sun is further evidence leading to the conclusion that the absorbed light is changed to heat.

The color of transparent objects can be explained in much the same manner. When one looks through a piece of common window glass or through a drinking glass filled with water, all the colors are transmitted, and hence the light is not changed. Such transparent objects are called colorless. If a piece of colored glass appears red, it is because the red from the white light that enters the glass is freely transmitted, while most of the other colors are absorbed. This can be shown by placing a piece of red or blue glass in place of the white screen in Figure 439. Although the prism separates the white light into its component colors, only the red band shows, while the others are absorbed. In a similar way green glass allows only green light to pass through; if we insert both the red and the green glass in place of the screen, all the colors are absorbed. We can summarize, then, by saying that color by transmission or reflection is the result of selective absorption. Light interacts with matter, and a certain part is taken out; the color which we see is what remains.

The Effect of the Source of Light

Thus far only the effect of the object was considered. It was assumed that the light was sunlight; that is, a light having all the colors. If the source of light is changed and an object is viewed by illumination from an electric light which does not have the same frequencies as sunlight, it is reasonable to expect that the color of the object will change. The degree of change will depend on the difference between the vibration frequencies of sunlight and of the electric light. To make the comparison extreme, let us suppose that we use light from a sodium-vapor lamp similar to the one used in lighting certain so-called "safety highways" at night. This light is yellow because it contains mostly waves of vibration frequencies

corresponding to the yellow band of the spectrum. When an object i illuminated with this yellow light, it will appear yellow if it can reflect thes wave lengths and dark if it cannot; therefore, a piece of yellow cloth wi appear yellow; similarly a piece of white cloth will appear yellow becaus white pigments have the property of reflecting all colors; but a blue o green cloth will appear dark. A room which is lighted by such light wi show all white objects as yellow and all red, blue, and green colors as black

From this brief discussion it appears important that any artificial ligh used for home illumination should be as nearly like sunlight as possible in other words, it should contain all the colors and in approximately th same intensity. The mercury-vapor lamp is deficient in the red wav lengths and therefore cannot be used, for all red colors would appear dark the light of the common tungsten electric lamp closely resembles sunlight but it contains more of the red, orange, and yellow. Therefore, thes colors are more prominent in a room lighted by the common tungsten fila ment bulb. If, however, the bulb is made of pale blue glass, some of th excess red, yellow, and orange is absorbed, while all the blue is transmitted Thus, the blue daylight lamp is a spectrum which closely resembles that o sunlight.

Color Vocabulary

It was previously stated that pure color is rare in nature, and that mos colors are mixtures. There are many shades of red, blue, and green; ther are shades of yellowish-green, bluish-green, and so on, which result fron reflection or transmission of not only the green but the other wave lengths There is a considerable want of method in naming colors. The commo vocabulary contains such shades as rose, cerise, mauve, heliotrope. It i possible, however, to refer colors and shades to the spectrum, as show qualitatively in Table 67 for a few combinations. By starting with th

Table 67. Summary of Colors

Pure colors	Mixtures of two colors	Mixtures of colored lights which produce white light	Mixtures of colored pigments
Red	violet-red	red + blue + green	yellow + red = orange
	orange-red	orange + green + blue	yellow + blue = green
Orange	red-orange	green + yellow + violet	red + blue = purple
	yellow-orange	yellow + blue	black + red = brown
Yellow	orange-yellow		black + orange = brown
	green-yellow		
Green	yellow-green		
	blue-green		
Blue	green-blue		
	violet-blue		
Violet	blue-violet		
	red-violet		

White opaque bodies reflect all colors. *Dark* opaque bodies absorb all colors. *Gray* opaque bodies reflect a por tion of colors with no predominance in any.

pure colors, which appear in the first column, it is possible to produce the mixtures which are shown in the second column. The proportion of each of the pure colors can be varied so that a large number of *hues* can be produced. Thus, red and orange may be mixed in a very large number of proportions; in the table only two such mixtures are shown, one in which the red predominates and another in which the orange is in excess. For each color or hue there are many *tints* and *shades*. These are obtained by variation of the intensity of color. If the color is diluted by admixing white the various tints are obtained; if any color, pure or mixed, is darkened (by diminishing the illumination), a variety of shades is produced.

In the third column of Table 67 are listed some pure colors which when mixed in the form of colored light give white color, and are called *complementary*. We can perform an experiment by red, green, and blue colored lights on a screen so that they overlap only in part. The portion in which all three colors are mixed, appears white, indicating that this combination produces the same effect as white light. The combination of red and green gives yellow, while that of red and blue gives violet. This indicates that the eye gives the sensation of a certain color, not only when it is stimulated by a wave length of the pure color, but also when it is stimulated by a mixture of wave lengths of two or more other colors. For instance, certain proportions of red and blue appear to the eye as the same color as that produced by pure spectral color violet. Likewise a mixture of red and green gives the same stimulus as pure (spectral) yellow. In the mixture of colored light used in our experiment we have only red, green, and blue, but since to the eye red + green = yellow, and red + blue = violet, the central patch contains all the colors of white light. Further examination of the colored screen will show that yellow and blue are complementary colors. Also, since violet may be considered to be red + blue, therefore violet + green + yellow will give white color. In other words, if certain colors are removed from the spectrum, the mixed colors that remain may be complementary and therefore produce white light.

A distinction should be drawn between mixing colored *light* — that is, light of definite wave lengths — and mixing colored *pigments*. If, for example, we mix chrome yellow with ultramarine blue, the result is not a white powder, but a green pigment. The explanation is not difficult to find if we recall the reason that pigments are colored. Pigments are opaque substances. Yellow pigments reflect only yellow and some green, while the rest of the colors are absorbed; blue pigments reflect only blue and some green. When both pigments are mixed, the only color not absorbed by one or the other pigment is green. Therefore, the color of a mixture of pigments is determined by the wave lengths of light which are not absorbed by the various substances in the mixture. The fourth column of Table 67 gives some of the general colors obtained by mixing the pigments commonly used for painting walls, houses, and pictures. But even

though pigments can defy the rule, the principle of complementary colors is still correct; for example, when one beam of light is transmitted through a yellow solution of sodium dichromate and an equal beam is transmitted through a blue solution of copper sulfate and the two beams are united on the screen, the compound color appears white. If, however, a single beam of light is passed first through one solution and then through the other, the compound color is green, as when we mix pigments, for now the only color which comes through is that which is not absorbed. In other words, when we mix opaque pigments, the process is subtractive, but when we mix colored light by superposition of one on the other, the process is additive. But it is possible even with pigments, if they appear in a very dilute form, to have the additive process and obtain white color. For example, the housewife, on rinsing the "washing," adds a small amount of "bluing," which combines with the yellow color of the linens and gives the appearance of white to washed sheets and pillowcases.

Color Vision

The human eye is sensitive to only a very small fraction of electromagnetic waves. The red waves correspond to nearly seven thousand Angstroms (0.00008 cm), and the violet to about four thousand Angstroms (0.00004 cm). As shown in Table 65, there are a large number of waves longer than the red and shorter than the violet which are not detected by the human eye; but a number of these can be detected by the photographic plate. Consequently, by means of a specially sensitized photographic emulsion, a picture can be taken with infra-red rays in a room which to the human eye is totally dark.

Even within the short range of visible light, all human eyes are not equally sensitive in the power of detecting color intensity. A number of persons have difficulty in distinguishing various shades and tints of red and orange, while others have poor responses to entire bands of colors; such deficiency is known as *color blindness*. The physiological basis for color vision is not known, although some speculations have been made.

The relation between frequency and wave length was considered in the discussion of sound. The low-pitch notes have a longer wave length and a smaller frequency than the high-pitch notes. Similarly, in light the red color corresponds to a longer wave length and a smaller frequency than the violet color. As shown above, the wave length of violet is one-half that of the red; therefore, the frequency of a vibrator emitting violet light must be twice that of one emitting a red light. But, while the human ear is sensitive to a wide range of frequencies, the eye is sensitive to a very narrow band. The audible tones vary from twenty to twenty thousand per second. The frequency of visible light varies from 4×10^{14} to 7.5×10^{14} per second. The range of audibility extends through eleven octaves, while the range of visibility covers but one octave of frequency. It should be

noted, however, that in the case of light the frequency is tremendous; in fact, it is impossible to visualize a vibrator with such a frequency. The source of these vibrations must be sought in the atoms and electrons of matter.

Color and the World We See

The phenomenon of color is associated with the sensation of color, but this, in turn, depends upon three distinct physical mechanisms, as briefly outlined below.

It was shown on page 802 that all materials when heated to high temperatures glow with a white light, or emit a continuous spectrum. An ordinary nail is visible at room temperature because it reflects light; it is not visible in a dark room. If it is heated gradually, it first glows dull red, and then the color changes in the order red, orange, yellow, and, near the melting point, white.

These colors are electromagnetic radiations of a comparatively narrow band of wave lengths (the visible spectrum) as received by the eye. But the green color of vegetation, as well as the colors of the pigments in a beautiful painting, for example, are the result of the *absorption* of certain wave lengths of light in the visible spectrum and the *reflection* of the remainder to the eye. From green leaves there is obtained a complex organic compound known as *chlorophyll*. It absorbs strongly the red end of the spectrum and some of the blue; hence most of the reflected light is the familiar green of the leaves. Similarly, from roses, lemons, and other plant tissues, pigments have been isolated which give them their characteristic colors.

There is still a third mechanism responsible for color. Thus we should not look for pigments in the plumage of a tanager or of a peacock, in the azure vault of the sky, in the rainbow, and in the clouds astride the setting sun. But in order to understand the colors of the world in which we live, we must take into consideration all the properties of light, including reflection, diffraction, refraction, and interference, for these properties contribute to the production of varied color in nature.

The color of the sky overhead on a clear day is a pale blue. In the early dawn the eastern sky assumes beautiful red and golden tints which change from minute to minute and vanish with the appearance of the sun. In the evening the western sky, particularly in summer and fall when there is dust in the air, is colored with brilliant red and golden tints after the sun has vanished beyond the horizon. After a shower, the rainbow, softly glowing with all the colors of the spectrum, arches above the horizon. The feathery clouds of fine weather are white, and the storm clouds are dark. These spectacles enter into every person's life and enjoyment, and are recalled in the songs and the literature of every nation. Let us see how they are to be explained in scientific terms.

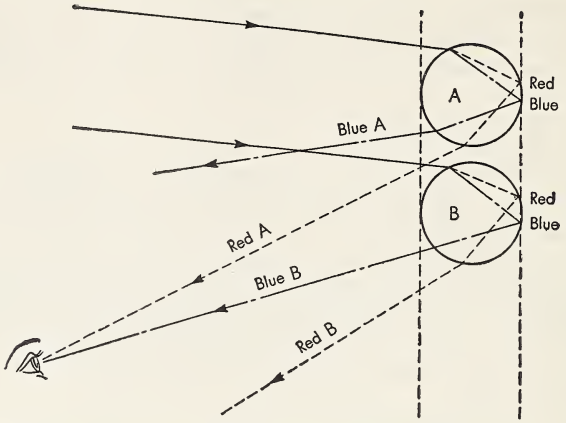

FIGURE 440. PATH OF RAYS THROUGH RAINDROPS

The light from the sun overhead is scattered by the particles of th atmosphere. These particles are the molecules of oxygen, nitrogen, wate vapor, and other components of the atmosphere, such as dust particles The blue rays, being of shorter wave length, are scattered to a greater de gree than the longer red rays. Since the blue is scattered most and th red least, the sky appears pale blue. If we ascend into the stratospher where there is a thinning-out of the gaseous components and very fe particles of dust, there is nothing for sunlight to fall on, no scatterin occurs, and the sky appears black. During sunrise and sunset, when th sun is at the horizon, the light waves must pass through a longer colum of the atmosphere than when the sun is higher in the sky. The blue ligh waves are scattered and absorbed, while the red and some yellow ones ge through to the eye, producing the brilliant hues we associate with the risin and setting sun.

The colors of the rainbow require a more involved explanation and ar produced mainly through the refraction of light by water drops. The rain bow forms when a cloud precipitates drops and is illuminated by the sun The rainbow when viewed by the observer is on the same side as th shadow; in other words, the observer stands with his back to the sun. Th rainbow appears as a colored arc of a circle. The colors, starting with re on the outer edge, appear as in the spectrum. A partial explanatio of the rainbow is indicated in Figures 440 and 441. Parallel rays fro the sun strike the raindrops in the cloud; the light rays are first bent (re fracted) as they pass into the drop, which acts as a lens and focuses ther upon its inner surface, which in turn acts as a mirror and reflects the ray

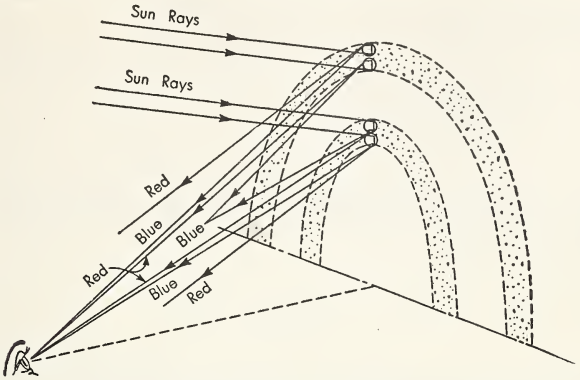

FIGURE 441. THE FORMATION OF A RAINBOW BY THE INTERNAL REFLECTION OF SUNLIGHT IN WATER DROPLETS

back; finally as they emerge they are bent (refracted) again. The blue rays are bent more than the red, and therefore the drop acts partly as a prism. Besides refraction and reflection there is interference, which complicates the succession of colors.

The color of clouds — white, gray, and black — may be similarly explained. The cirrus (high) clouds are white because the fine ice needles which make up the clouds reflect the light; the nimbus (rain) clouds are black because they absorb most of the light. Smoke from the chimney of a boiler that has just been fired is black because it contains large carbon particles which reflect no light; after some time the smoke may appear gray or even bluish because there is scattering of light by the finer particles of carbon and droplets of water vapor. The colors of most feathers are due to light interference similar to that produced by soap bubbles and other films.

SUMMARY

1. White light is composed of several pure colors.
2. A pure color is one that is produced by waves which have but one vibration frequency; colors in nature are usually mixtures of two or more pure colors.
3. The color of an opaque object depends on its selective absorption of light; a certain part of light is taken out and the part reflected determines the color of the object. The color of transparent objects depends on the part which is not absorbed, but is transmitted.
4. The color of all objects that have no light of their own depends also on the nature of the light falling on them.

5. Complementary colors when mixed give white light.
6. A mixture of two colored lights can produce the same color stimulus in the eye as that produced by a pure spectral color. Color vision among various people varies within wide limits.
7. The color of a substance, whether opaque or transparent, depends on the chemical structure of that substance.
8. The colors that we see about us depend on other factors besides selective absorption of light. Other properties of light waves — such as reflection, diffraction, refraction, and interference — contribute to the production of varied color in nature.

STUDY EXERCISES

1. Mark with the letter *A* if the statement is true of visible light; *B* if it is true of light of higher frequency than visible light; *C*, of lower frequency; *D*, if true of all radiation:
   .... affects the ordinary photographic emulsion when it falls directly upon it.
   .... affects the photographic film which is wrapped in dark paper.
   .... can be resolved into various colors.
   .... ionizes air and causes emission of electrons from active metals.
   .... travels at a speed of 186,000 miles per second.
   .... can be detected through sensitive thermometers or tuned circuits.
   .... can be reflected and refracted.
   .... can easily produce sunburn on human skin.
   .... is involved in photosynthesis.
   .... consists of electromagnetic waves.
2. When white light is allowed to pass through a glass prism, it is resolved into several different colors. Place the first letter(s) of the color(s) which best complete(s) the following statements:
   .... the complementary of orange.
   .... when mixed in the form of pigments give black, but when mixed in the form of light give white.
   .... when mixed in the form of light, give white; when mixed in the form of colored pigments, give dark green.
   .... reflected by a white surface and absorbed by all others except blue and green.
   .... absorbed by red glass.
   .... reflected by red cloth.
   .... transmitted through a solution of chlorophyll.
   .... the complementary of red.
   .... predominant in the sodium flame.
   .... absorbed by leaves in photosynthesis.
3. Assume that you are looking at a sunset; later you examine a painting of a sunset; still later you observe on the screen a colored movie of a sunset. Explain in each process the mode of color production.

4. Illumination involves both the source of light and the reflecting surfaces. Construct a table giving such information covering this as is needed in order to obtain the following effects: (*a*) to illuminate a room used for matching shades of fabrics; (*b*) to illuminate a reading room; (*c*) to illuminate a stage representing a seashore. Explain in each case the reasons for your selection.
5. Red and green colors are used in traffic signals. Give some of the reasons for their use.
6. In the following explain very briefly the cause of color: (*a*) the color of a white rose; (*b*) the color of a red rose; (*c*) the color of red human hair; (*d*) the color of white human hair; (*e*) the colors of the rainbow; (*f*) the colors of a robin.
7. Coal is black; when it is distilled it gives among other products black coal tar; from the coal tar are obtained benzene (C_6H_6), toluene ($C_6H_5CH_3$), naphthalene ($C_{10}H_8$), etc. All these substances are colorless. Starting with these substances, it is possible by appropriate chemical reactions to produce colored substances and dyes.
   (*a*) What is the difference between a colored substance and a dye?
   (*b*) Name some groups which, when present in organic compounds, cause the absorption of certain colors.
   (*c*) Why are synthetic dyes at times called aniline dyes?

FOR FURTHER READING

1. Bragg, W., *The Universe of Light.*
   An excellent book on light and color. Chapters 1–4 are recommended for the general student.
2. Luckiesh, M., *Color and its Application.* 2d edition; New York: D. Van Nostrand Company, 1921.
   A non-technical book on color and its application.
3. Eyring, C. F., *A Survey of Physics.*
   A discussion of color will be found in Chapter 13.
4. Taylor, L. W., *Physics.*
   A discussion of color will be found in Chapter 33.
5. White, H. E., *Classical and Modern Physics.* New York: D. Van Nostrand Company, 1940.
   A good non-technical discussion on color will be found in Chapter 25.

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Theories of Cosmogony

UP TO THE PRESENT our story of the physical world has been primarily one of matter and energy. We have seen how man, with his inherent desire to know, to understand, and to use, has gradually developed the sciences. He has designed instruments and techniques which have greatly widened his field of observation, especially during the past few hundred years. With these tools the earth with its matter and its energies has been closely examined. Telescopes have been turned toward our neighbors in the solar system and toward the more distant bodies, the stars and galaxies. The knowledge thus obtained has been evaluated and classified; laws and principles, hypotheses and theories have been formulated by the rigorous application of the scientific method.

But we are not satisfied to know something of the nature of matter, the forms of energy, and the laws which govern the universe. We ask how and when did it all start? And what took place on the earth during that long sweep of time before man appeared and developed sufficiently so that he could leave some record of his observations? We shall therefore close our story with an endeavor to answer these questions in so far as science can do so. In this chapter we shall estimate the age of the earth and show how the solar system may have originated. In the following two chapters we shall outline the history of the earth as reconstructed by the geologist from the knowledge he has been able to derive from the earth's crust.

The human mind is interested in origins — the origin of life, of man, and of the astronomical bodies. So universal is this interest that every culture and clan has its legend or tradition of creation. However, no plausible attempts to formulate a scientific hypothesis concerning the origin of the earth and the solar system were made or could be made until accurate observational and mathematical astronomy was developed in the eighteenth century. But before we present pertinent facts of astronomy, geology, and certain physical principles which any hypothesis on the origin of the solar system must explain, we should point out that such hypotheses

do not attempt to establish ultimate origins. If our solar system was born of the sun, or of a dust cloud, then where did the sun originate? If the sun or cloud is an offspring of one of the galaxies, we must ultimately encounter what the philosophers call the first cause or the uncaused cause. Either the solar system has always existed as it is at present, or at some time in the remote past it was quite different from its existing state. All theories that deal with a cosmogony — or the origin of the solar system — assume that the latter postulate is true and that the sun is either the parent body or of common origin. Our first problem is to attempt to determine how long the solar system has existed and for the answer to this question we obviously turn to the earth.

How Old Is the Earth?

In attempting to determine the age of the earth one must seek some process of change which may be assumed to have continued at a constant rate without interruption since the present crust of the earth has been in place. Many methods — all based upon our knowledge and observation of changes which are taking place and which have taken place in the recent past — have been employed. Most of them are not even approximately quantitative and serve to indicate only that the earth is very old — much older than was believed until recently. We shall consider several of these methods.

1. *The rate of deposit of sedimentary rocks.* In 1854, the base of a large statue of Rameses II was found under about nine feet of sediment deposited by the Nile River. The statue is at least three thousand years old, so that the average rate of deposit for that period and place is three-tenths of a foot per hundred years. At this rate, which is certainly not typical of the rate of sedimentation over the entire surface of the earth, the formation of the estimated hundred-mile covering of sedimentary rock required more than a hundred and fifty million years. Banded shales (consolidated clays), like those in the Green River lake deposits of Colorado and Wyoming, show seasonal markings which permit a more accurate and direct estimate of the time required for their deposit. A half-mile of such material is thought to have been deposited in six and a half million years. At this rate the sedimentary covering of the earth would have required thirteen hundred million years of constant and uniform deposition. This method has a number of defects for, although it is useful in computing the time required for the deposition of certain specific sedimentary formations, it is inadequate to serve for all geological time. Deposition did not begin when the earth was formed, for the process requires seas and atmosphere which appeared later. Nor is deposition a continuous process after it starts. There have been times when rocks were uplifted and eroded as shown by unconformities — the gaps in geological history.

2. *The rate of erosion of the continents.* Estimates of the yearly amount

of material carried into the ocean, both in solution and in suspension, indicate that in ten thousand years a one-foot layer of the surface of the North American continent is removed. In the past the continents have been successively elevated and submerged. Rather recently they have been elevated; and the present rate of erosion is therefore higher than average, but we have no way of finding how much higher. Our estimate of the age of the earth on the basis of this variable process can yield only conjectural results.

3. *The salt in the sea.* In the process of erosion and weathering, soluble salts are formed and these ultimately are carried to the oceans where they remain in solution. The volume of the ocean water has been computed with fair accuracy and the total salt content determined. By dividing the salt content by the estimated annual increase, a figure slightly in excess of one hundred million years is obtained. As with the preceding estimate, the process must have been a highly variable one, and man's observations extend over too short a period to be used as an average for geological time.

4. *Tidal effects.* The tidal effect of the moon (see page 295) has been shown to brake the earth and slowly retard its rotation. The moon moves farther and farther away from the earth. This effect and motion have been mathematically traced backward in time to the period when the moon was so near the earth that it was at the point of falling into it. The earth-moon system and the seas on the earth have existed, according to the computations based on the assumption of constant tidal friction, not more than four thousand million years.

5. *Radioactivity.* We have seen (Chapter 24) that the naturally radioactive elements disintegrate, expelling alpha particles (He^{++}), beta particles (electrons), and gamma radiation at a constant rate irrespective of conditions of temperature and pressure. No physical agency can speed or retard this disintegration in the slightest degree. The end product of the radioactive decay is lead and a by-product is helium. In a sample of uranium (half-life 4.51×10^9 years), about one sixty-seventh of its atoms would decompose in a hundred million years and an equal number of atoms of lead would result as the end product. The lead so obtained has an atomic weight of 206, while that of ordinary lead is 207.2. Thorium, another radioactive element (half-life 1.39×10^{10} years), yields lead of an atomic weight of 208. An isotopic analysis of a sample of uranium bearing rock tells us the amount of uranium present and the amounts of the different forms of lead. From the lead (206)-uranium ratio and the half-life of uranium the age of the rocks can be calculated. In some rocks the crystals contain enclosed helium, but determinations based on the helium-uranium ratio give ages which are lower than indicated by the lead content. This may be explained by the fact that helium is a gas and is likely, in the long interval, to have diffused through the crystals. The age of the oldest rocks

is estimated by this method to be about eighteen hundred million years. The earth has been solid at least as long as this, but is evidently still older. From an analysis of ordinary rocks for uranium, thorium, and all lead, the maximum figure is computed to be three thousand million years. This assumes that all the lead present came from the radioactive elements. Actually, the age is probably less, for some of the lead may have been already present. Iron meteorites have been analyzed for helium, and the minimum and maximum ages obtained for these bodies are, respectively, sixteen hundred million and twenty-five hundred million years. These methods, together with certain other astronomical methods, fix the age of the earth as between two thousand million and three thousand million years.

Relevant Facts Concerning the Solar System

There are a number of features of the solar system which must be explained or embodied in any theory of its origin. The system is *complex*, consisting of the sun, nine major planets, twenty-eight satellites which revolve about six of the planets, about fifteen hundred planetoids whose orbits are known and tens of thousands of others, about a thousand known comets and probably thousands more, and an immense number of meteors. The system is somewhat *isolated*, as, indeed, other stars and possible systems appear to be. The time required for light to travel from the nearest star (Proxima Centauri) to the sun or earth is 4.2 years; but less than five and one-half hours are required for it to travel from the sun to the outermost planet, Pluto.

Regularities. For all its complexity, there is a regularity and an organization among the major bodies of the solar system which is not due merely to chance. The regularities, some of which are discussed in Chapter 16, are:

(1) The planets and nearly all the planetoids revolve around the sun in the same direction and with their orbits all in practically the same plane. The orbits of the planets are ellipses of low eccentricities (nearly circular), with the exception of those of Mercury and Pluto. Some of the planetoids move in highly eccentric orbits and in planes which are greatly inclined to the plane of the planetary orbits.

(2) The sun rotates in the same direction as that in which the planets revolve, and the plane of its equator nearly coincides with the planes of the planetary orbits.

(3) The mean distances of the planets from the sun, with some exceptions, follow the Titus-Bode law. This regularity may be approximately shown by listing a series of 4's, and adding successively the numbers 0, 3, 6, 12 — each number after the second being twice the preceding one. The result divided by 10 gives the mean distance of the planet from the sun in astronomical units:

Mercury	*Venus*	*Earth*	*Mars*	*Asteroids*	*Jupiter*	*Saturn*	*Uranus*	*Neptune*	*Pluto*
4	4	4	4	4	4	4	4		4
0	3	6	12	24	48	96	192		384
4	7	10	16	28	52	100	196		388
0.4	0.7	1.0	1.6	2.8	5.2	10.0	19.6		38.8

The ninth term of the series represents the mean distance of Pluto rather than that of Neptune, while the fifth term gives the average distance of the asteroids. Upon comparison of the above figures with the actual distances of the planets and the asteroids (average), a fairly close agreement is observed:

0.39	0.72	1.00	1.52	2.80	5.20	9.54	19.19	30.07	39.5

(4) The satellites revolve about the planets in the direction in which the planets rotate, except for three moons of Jupiter, one of Saturn, and that of Neptune, which revolve in a retrograde direction. Their orbits are nearly circular and in most cases lie in or very close to the plane of the planet's equator.

(5) The four inner planets are separated from the outer planets in space and differ from the latter in that they are smaller, possess fewer satellites, have lower velocity of rotation, and have higher densities.

Distribution of Mass and Angular Momentum. It will be shown later that a number of hypotheses have been abandoned because they failed to explain the distribution of the angular momentum in the solar system. For a body revolving about a point, this quantity, also called moment of momentum, is the product of the mass of the body, the velocity, and the distance from the body to the point around which it is moving. If the motion is a circle, this distance is the radius.

$$\text{Angular Momentum} = m(\text{ass}) \times v(\text{elocity}) \times d(\text{istance})$$
$$\text{or} \qquad M = mvd$$

The angular momentum of a planet due to its revolution, therefore, is equal to its mass times its orbital velocity times its distance from the sun, if we assume a circular orbit with the sun at the center. The angular momentum due to rotation is the sum of the momenta of all of the particles in the body.

In the solar system the sun possesses 99.866 per cent of the mass of the system, but less than 3 per cent of its angular momentum. The planets with less than 0.14 per cent of the mass have more than 97 per cent of the angular momentum, and of this total Jupiter has nearly 60 per cent. In any isolated system — that is, a system which cannot be acted upon by some external force — the angular momentum is conserved and is therefore a constant. If, for example, a rotating body should shrink, it would

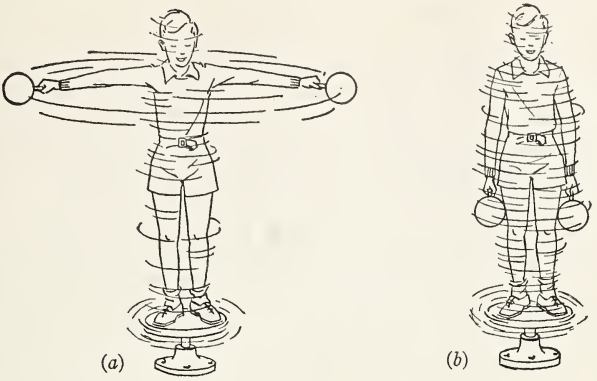


FIGURE 442. CONSERVATION OF ANGULAR MOMENTUM (mvd)
When the arms are dropped on both sides, d is decreased and a corresponding increase in the velocity of rotation (v) is noted.

rotate faster. To illustrate this principle, one may hold weights or heavy objects in each extended hand and be rotated on a turntable (Figure 442, *a*). When the hands with the weights are dropped to the side, the rotation becomes faster (Figure 442, *b*). Since mvd (with hands extended) = mv_1d_1 (hands at side), $vd = v_1d_1$ and $v/v_1 = d_1/d$, or the velocity of rotation becomes greater as the average distance, or radius of rotation, becomes less. For a revolving body the principle may be illustrated simply by whirling a weight on a string so that the string winds around a finger (Figure 443). As the string becomes shorter (d becomes less), the weight

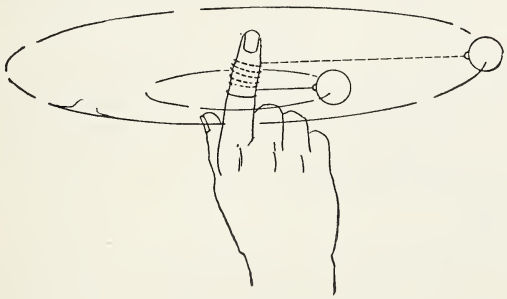


FIGURE 443
CONSERVATION OF ANGULAR MOMENTUM IN A REVOLVING BODY
As the string wraps itself around the finger the weight moves faster and faster.

revolves faster (v becomes greater), and the quantity mvd remains constant.

Chemical Constitution. It was formerly believed that the sun and other stars were composed of the same proportions of chemical elements as the earth. However, more recent estimates, based on extensive spectroscopic data, indicate that the common elements which form the body of the earth constitute only about one per cent of the mass of the sun. The rest of the sun is composed almost entirely of hydrogen and helium. It is also known that in interstellar space there are great clouds of fine dust and gas, very diffuse and of less density than the highest vacuum which has been produced on the earth. So great is the interstellar space, that the total mass of this material is probably equal to that of all of the stars. This material consists almost entirely of hydrogen and helium, with a small fraction of the heavier terrestrial elements.

On the other hand, it has been shown that the gaseous elements (hydrogen, helium, and the other inert gases) are less abundant in the earth than one would expect from the above data. The faster-moving hydrogen and helium molecules could have evaded gravitational capture by the earth, or, if on the earth, could have escaped at temperatures of a few hundred degrees. The low abundance of the heavier gases can be explained only by assuming that the earth was at one time of considerably less mass than at present.

The material of the earth is stratified (pages 208–211) with a very dense core and the stratification may have been caused by chemical changes leading to the formation of heavier substances, and to plastic flow, both due to the enormous pressures in the interior.[1] It has also been shown that the meteoritic matter in the solar system is of about the same composition as the earth and that the substances in the meteorites may well have been under the high pressure of a planet's interior.

With the above facts and principles as a basis, a number of hypotheses on the origin of the solar system may be considered. All hypotheses on cosmogony start with the sun or with a gas dust cloud from which the sun and the planets were formed. They may be divided into two classes: the *dualistic* or catastrophic hypotheses, which assume interaction of the sun with other stars or celestial bodies; and *monistic* or uniformitarian, which assume that the solar system developed as a closed system, isolated from other similar groups in the universe.

Dualistic Hypotheses

Hypotheses in this class, which at present are *not* generally accepted, start with the sun and postulate a close encounter or collision of another body with the sun. It was thought by those who speculated along this line that the unequal distribution of angular momentum (page 832) in the solar

[1] It is therefore no longer necessary to assume that the earth was at one time molten.

system could be accounted for only by assuming that a second star passed near by or sideswiped or collided with the sun. Matter was thus pulled or knocked from the sun, given momentum, and later somehow was condensed or gathered together in masses which became planets.

The idea of interaction with an outside body was proposed in 1749 by George-Louis Leclerc, Comte de Buffon, a French naturalist, who suggested that a comet may have collided with the sun, tearing from it the planetary material. This idea received little attention at that time. In 1900 T. C. Chamberlin and F. R. Moulton, both of the University of Chicago, announced the *planetesimal hypothesis*, which postulates that a star moving in a curved path came very close to the sun.

Gravitational pull, aided by great disruptive forces within the sun, caused the ejection of material from the latter in successive bolts, on the side near the star as well as on the side opposite to the passing star. (See Figure 444.) The hot solar material then condensed into solid particles or planetesimals of different sizes which moved around the sun in a common plane and in elliptical orbits. The more massive bodies swept up the smaller ones by their greater gravitational attraction to become the planets. Variations of this hypothesis, involving the collision of as many as three stars, were later proposed by Sir James Jeans and Harold Jeffreys, H. N. Russell, R. A. Lyttleton, and others.

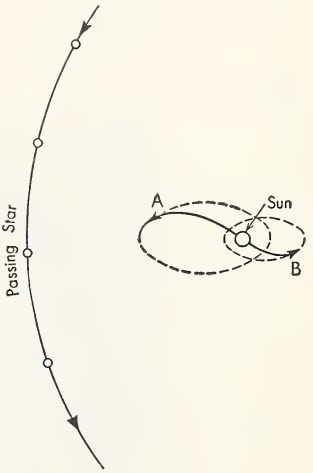


FIGURE 444
THE PLANETESIMAL HYPOTHESIS

A passing star drew successive bolts or masses from the sun as the two bodies passed each other. Diagram shows the progress of the tidal disruption to produce mass A which became an outer planet and mass B which became a terrestrial planet.

The principal defect of the collision or near-collision hypotheses was shown by Lyman Spitzer in 1939. The hot gaseous material of the sun is held together by enormous gravitational forces due to the sun's great mass and is prevented from collapsing into a more dense mass by its temperature (40 million degrees at the center). Spitzer showed mathematically that if some of this material were suddenly removed from the sun and thereby released from the enormous gravitational forces, it would expand with terrific force and most of it would escape from the region now occupied by the planets. It is unlikely that the material remaining would condense and coalesce into masses of planetary size.

Monistic Hypotheses

Hypotheses in this category start with a rotating gaseous nebula, eithe with a sun surrounded by a rotating gaseous cloud, or with a cloud of ga and dust particles, and assume that the solar system developed withou any interaction with other celestial bodies. The troublesome distributio of angular momentum must therefore be explained by processes which tak place in a closed system. After it was shown by Spitzer and others that th two or three star hypotheses were no longer satisfactory, an idea developed by Immanuel Kant in 1755 and a little later extended by Laplace was revived.

Kant, inspired by Thomas Wright's theory of the milky way, developed deductively the hypothesis that the solar system evolved from a great mass of gas or nebula. This mass occupied the entire volume of the present solar system, and because of gravitational attraction the heavier particles or molecules attracted and absorbed the lighter ones. The collisions of these particles generated heat and motion, so that the nebula began to rotate. As the speed of rotation increased, splashes of matter were thrown from the equatorial region, forming rings which finally condensed to form

FIGURE 445. PIERRE-SIMON, MARQUIS DE LAPLACE
1749–1827

(From D. E. Smith's "Portraits of Eminent Mathematicians," published by Scripta Mathematica, New York City)

the planets. Although Kant's idea was not accepted at the time, due to certain dynamical defects, it has recently been revived on a more scientific basis. Kant also made a number of assumptions regarding Saturn's rings, the zodiacal light, and the tidal effects of the moon, which later received remarkable confirmation.

The Nebular Hypothesis

The renowned French mathematical astronomer, Laplace (Figure 445), formulated on a more scientific basis an hypothesis very similar to the idea developed by Kant. The *nebular hypothesis*, as it was called, was outlined briefly in a popular book on astronomy, *Exposition du Système du Monde* (1796). The idea attracted considerable attention, both because of the great prestige of Laplace and because it was introduced during a period of great social and scientific revolution. Widely accepted for more than a hundred years, it stirred the imagination and was the stimulus to other theories of evolution, particularly in the biological sciences.

The nebular hypothesis assumed that the material which now comprises the solar system was once an extensive gaseous body or nebula (see Kant's hypothesis) which was originally at a high temperature, and which rotated on its axis. As it lost heat by radiation, it contracted, and by the principle of conservation of angular momentum, the mass rotated faster and faster. So great was the speed of rotation that an equatorial bulge developed; when the centrifugal force at the equator became equal to the gravitational attraction a ring of matter, bulging in one place, was left behind. As the remaining mass contracted further, the process was repeated, and more rings were successively shed (Figure 446) with considerable time intervals between. In all, ten such rings were lost, and the remaining material comprised the sun. The matter in each of nine rings in some manner gathered together or coalesced around the bulge to form a planet. One ring broke up to form the planetoids, which, for the most part, are in the space between Mars and Jupiter. The planets, still in the gaseous state, rotated, and some of them shed more rings which coalesced to form the satellites. Ultimately, the matter in the planets condensed and solidified.

The hypothesis accounts for the direction of rotation of the planets and their satellites, which is the same as the rotation of the sun, and for their nearly circular orbits, the planes of which closely coincide with the equatorial plane of the sun. It received support also because of the existence of nebulae which at that time were not known to be so extensive as to contain the mass of millions of suns, and which appeared to be replicas of the hypothetical parent gaseous mass. The rings of Saturn, which we now know are stable and apparently permanent, were cited as similar to the rings postulated by Laplace.

However, the nebular hypothesis does not account for the retrograde

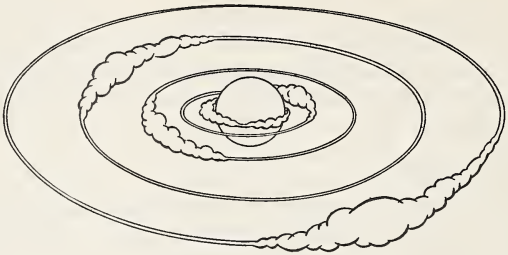


FIGURE 446. THE NEBULAR HYPOTHESIS

A great rotating nebula successively shed gaseous rings which condensed into the planets. Some of the planets lost smaller rings, which became satellites.

motions of certain satellites; nor does it explain how a satellite may revolve faster than its principal rotates, as does Phobos, a satellite of Mars. The chief objection to the hypothesis was that it did not explain how the sun, with most of the mass of the system, had so little of the angular momentum.

It should, according to the hypothesis, rotate very rapidly, and continue to shed rings, or at least have an equatorial bulge; instead it rotates only once in twenty-eight days. Yet, if the sun had all of the mass and angular momentum of the solar system, it would be less flattened at the poles than some of the planets. Clerk Maxwell, who gave the hypothesis a mathematical treatment, showed that the rings thrown out from the sun would remain permanent like the rings of Saturn.

Alfvén's Hypothesis

The Swedish physicist H. Alfvén proposed in 1942 a cosmogony which takes into account the magnetic field around the sun, an idea which previously had been suggested by Birkeland in Norway and by H. P. Berlage, a Danish meteorologist. The sun's magnetic field exerts a greater force on electrically charged matter in the regions of the solar system than that due to the gravitational pull of the sun. Alfvén suggested that at one time the sun was surrounded by an interstellar gas cloud. Attracted by the gravitational force of the sun, the atoms in the cloud fell toward the sun with increasing velocities. At high speeds some of the atoms became ionized by collision with others. As soon as an ion was formed, its fall toward the sun was retarded and it moved along the magnetic field of the sun to an equilibrium position. By this mechanism a great amount of matter was concentrated in the equatorial plane of the sun. This matter condensed to form the planets. This process may possibly explain the formation of the outer planets, but not the inner ones. Ionization took place at too great a distance from the sun to permit a concentration of matter in the regions where the inner planets now exist. Alfvén suggested that the sun may

have encountered a smoke cloud of small solid particles which vaporized when near the sun. The resulting atoms may similarly have become ionized and by the same mechanism described above, matter was concentrated nearer the sun to form the inner planets.

In criticism of this interesting possibility, it has been shown that if enough matter were concentrated in a gaseous cloud around the sun to form the planets, the free movement of the atoms would be so retarded that very little ionization would take place.

The Dust Cloud Hypothesis

In 1948 Fred L. Whipple of Harvard University introduced a new idea to account for the origin of the stars and planets. He suggests that the sun and planets were formed from a great cloud of dust and gas. That such clouds exist today is shown by the scattering of light of distant stars which passes through them. Lyman Spitzer suggests that the feeble pressure exerted by light forced the dust particles into clouds just as it forces the fine material in the tail of a comet away from its head and from the sun. Two dust particles may be drawn together because of the lower light pressure in the shadow between them (Figure 447), forming a larger particle which casts a greater shadow. A small cloud may form, and, because of the larger shadow, draw in the smaller particles around it, finally growing to such a mass that its gravitational effect is greater than the light pressure. A dust cloud of the same mass as the sun and with the two forces balanced would have a diameter of about 6×10^{12} miles.

As suggested by Whipple, such a cloud, which may have acquired more mass, began to condense under its own gravity. While the material in the cloud had some random turbulence, the mass as a whole had practically no rotation nor angular momentum. It contracted, slowly at first because of the motions of the streams of dust within it, but in the course of some millions of years these motions were arrested by friction and collision. As it became smaller, its density increased, and consequently the force of gravity within it became greater. It finally collapsed at a very rapid rate, the temperature increasing due to the pressure within the cloud, until it reached millions of degrees — enough to initiate the chain of nuclear reactions with helium, hydrogen, and carbon. In this manner the hot radiating sun was formed.

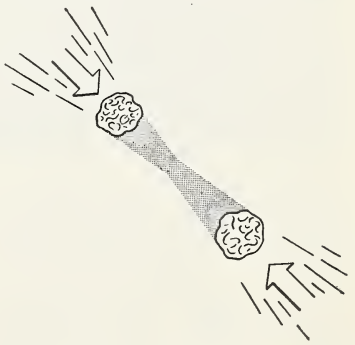
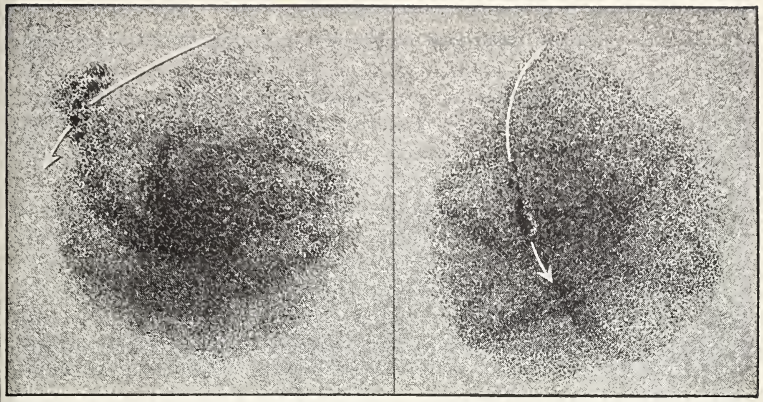


FIGURE 447. RADIATION PRESSURE

The planets evolved from the same great cloud during the shrinking processes which resulted in the formation of the incandescent sun. During the very early stages of contraction, streams of dust developed in the cloud. The dust had become so dense and concentrated in the largest stream that it condensed into smaller clouds which moved along with the main body. These smaller clouds grew by gathering up the less concentrated material and became *proto-planets*. These masses of a variety of sizes and speeds began to spiral in toward the center of gravity of the system. Some of them may have reached the center of the mass to become part of the sun. But in the meantime the stage of rapid collapse described above was reached, and a number of the proto-planets were left moving in orbits around the sun. These masses condensed to form the planets, but as they had less mass than the big cloud, they did not attain by contraction a sufficiently high temperature to initiate the nuclear reaction (Figure 448). In a similar manner the satellites may have been formed by condensation of the outer cloud of material which remained when a proto-planet collapsed to form a planet. This assumption is supported by the fact that with the exception of the earth-moon system each planet has a very much greater mass than that of all its satellites.

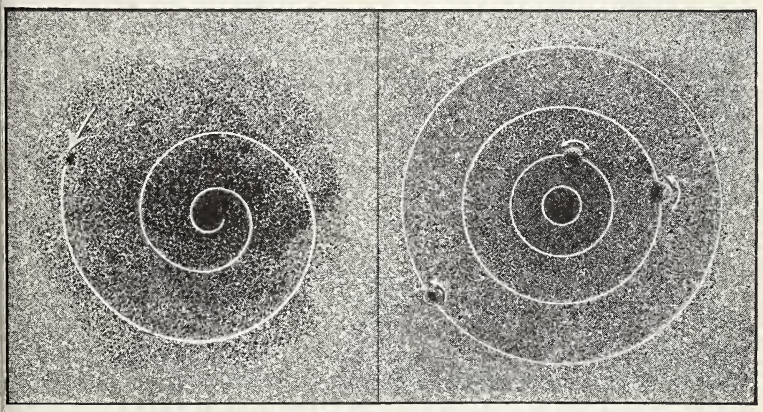
Many of the properties of the solar system are accounted for by the dust-cloud hypothesis. The newly formed planets were initially very hot and some were probably molten; this would account for the density stratification in the earth. The slow rotation of the sun and the large angular momentum of the planets is explained by the lack of rotation in the original great cloud and the spiral-like motions of the dust streams which formed the planets. As in a number of hypotheses, the chemical constitution of the system is accounted for by the failure of the less massive planets to hold by gravitational attraction very much of the light gases (hydrogen and helium) which pervaded the dust cloud.

The regularities of the solar system, with the exception of the Titus-Bode law, are explained satisfactorily. The path of the original stream of dust determined the direction and the plane of revolution of the planets. That the nearly circular orbits of the planets are the result of the initial spiral motion, assumed in this hypothesis, is in accord with mathematical theory. The rotation of the planets is due to the increasing density of the condensing cloud into which they spiraled. The cloud was more dense toward the center, and as a proto-planet moved in, it encountered more material on the inner side, which became heavier and was slowed up. The outer side moved faster and the whole body thus acquired a forward spin or rotation. The larger planets had a greater difference in the density of the medium on their inner and outer sides, and therefore acquired greater rotational speed. The small sizes and the fewer satellites of the inner planets are due to their close proximity to the sun. They were probably within the outer fringes of the hot condensing sun, and the material which



(*a*) *In the great dust cloud formed under the influence of light pressure, streams of dust developed and began to move under the force of the cloud's gravity.*

(*b*) *The major stream of high density condensed into smaller clouds or proto-planets, and these began to move in toward the center of the large cloud.*



(*c*) *The proto-planets spread out and continued to spiral inward as the large dust cloud began to contract.*

(*d*) *As the contraction continued, some of the proto-planets moved in circles within the cloud, acquiring a rotary motion as they picked up more matter on the side toward the center of the cloud.*

FIGURE 448. FORMATION OF PLANETS IN DUST CLOUD

(*Courtesy of "Scientific American"*)

might have formed satellites was evaporated away. They were also perhaps smaller to begin with and, unlike the more massive and less dense outer planets, unable to hold the lighter gases by gravitational attraction.

The asteroids which move in the region between Mars and Jupiter are probably the pieces of a broken planet which may have collided with another planet moving in a highly eccentric orbit. It has been calculated that the planet was about the size of Mars.

The explanation for the retrograde motion of several satellites is the same as that offered in the gaseous tidal hypothesis — they may have been captured from one planet by another.

The dust-cloud hypothesis is compatible with most of the facts, but shares a serious weakness with a number of other hypotheses of this group. It is difficult to explain how a nucleus may form in a very rare gas dust cloud and hold itself together in the early stages and then acquire sufficient mass to attract other material by gravity.

Von Weizsäcker's Hypothesis

In 1943 the German physicist, C. F. von Weizsäcker, proposed an hypothesis for the evolution of the solar system based upon the newer knowledge of the chemical composition of the sun (page 833) and upon a theoretical treatment of the dynamics of large masses of gas. He suggested that the sun was formed by the condensation of interstellar matter which was in a state of turbulent motion, and that the newly formed star was enveloped by a cloud of gas and dust. This envelope had an angular momentum due to rotation and as a result of this motion assumed a disc-like shape. The material in the disc, whose mass was perhaps a hundred times that of the present planets, consisted mostly of the gases hydrogen and helium, and fine dust particles of solid terrestrial materials such as metallic oxides, silicon dioxide, and water. The fine dust was carried along by the moving gas.

The disc was not stable, for, in accordance with Kepler's third law, the angular velocities of its parts decrease with the square root of the distance from the sun. These different velocities created "frictional" or viscous forces which would tend to make the disc rotate as a whole rigid body. The inner or faster moving parts were decelerated and moved toward the sun; the outer parts were accelerated and moved outward into space. The energy consumed by those motions and by the viscous forces was provided by the gravitational energy released by the matter which fell on the sun. Angular momentum was therefore transferred from the inner to the outer part of the system. To explain the distribution of angular momentum in the system and the slow rotation of the sun, von Weizsäcker assumes that the material which fell on the sun had zero angular momentum and that which moved into interstellar space had most of the angular momentum. He further assumes that the material which escaped into space was of

low atomic weight, thus accounting for the great difference in chemical composition and density between the planets and the sun.

The fine dust which was distributed throughout the space now occupied by the system was aggregated into the big masses which are now the planets. This growth into masses started by collision. It is evident that if two particles which collide are of approximately equal mass they would pulverize each other; if one is larger than the other, then the smaller would bury itself in the larger, adding to its mass. Nuclei so formed grew by collision and after attaining considerable mass, grew by gravitational capture of the smaller masses. In the growth by accretion, the bombardment of the masses by dust and larger particles kept the planetary bodies at a very high temperature, and their surfaces cooled by radiation only when the interplanetary material was practically all consumed.

Had the growth by collision described above been due to random unorganized motions of the particles, one large planet might have resulted rather than the nine planets spaced in accordance with the Titus-Bode law stated earlier in this chapter. However, as the particles of the dust cloud moved around the sun in elliptical orbits of various sizes and eccentricities, there were an enormous number of collisions. As a result the motions became somewhat organized; those having the same periods of revolution around the sun maintained the same average distance from that body. Von Weizsäcker was able to show that a regular system of bean-shaped vortices (Figure 449), in which the particles moved as the disc rotated, is possible. If the direction of rotation of the disc was counterclockwise, the motion in the vortices was clockwise. Along the circles where the rings of the vortices met, secondary eddies were set up and collisions occurred, resulting in aggregation and growth to form the planets. It may be shown mathematically that the radii of the successive rings constituted a simple geometrical progression which is approximately in accord with the Titus-Bode law and the distances of the planets from the sun. The resulting planets retained some of the dust cloud, and the satellites were formed in a similar manner.

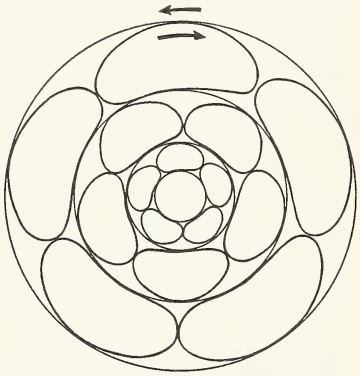


FIGURE 449

VORTICES IN GAS-DUST CLOUD

Planets grew by accretion along circles where the rings of the vortices met.

While there is some criticism of this hypothesis, it probably accounts for

more of the observed facts than any of the other hypotheses. It has been suggested that the deceleration of the sun to its present period of rotation cannot be accounted for by the matter with zero angular momentum which it attracted from the cloud. The separation of the elements according to atomic weight and angular momentum has also been questioned. It is, however, in accordance with kinetic principles that the lighter gases (hydrogen and helium) which constituted the bulk of the disc would escape either to the sun or to interplanetary space.

D. ter Haar, who made some of the above criticisms, has attempted to make a detailed investigation of the properties of a rotating gas cloud, which according to some of the hypotheses, may have originally enveloped the sun. While a detailed discussion of his conclusions cannot be given here, a few of his pertinent conclusions concerning the condensation of the material in the cloud may be mentioned. The temperatures on the gaseous disc would decrease as the distance from the sun increased. Fewer substances would therefore initially condense in the regions nearer the sun; that is, only inorganic compounds would condense in that part of the solar system where the terrestrial planets now exist, while in the portions where the outer planets are found both inorganic and organic compounds, which are more volatile, would condense. As a result, the part of the system near the sun should have fewer nuclei for condensation than the outer regions, and these should be more dense. It follows that planets formed in the inner regions should be smaller and more dense than those in the region farther from the sun. These predictions are in accordance with the facts. The outer planets are larger and less dense than the terrestrial planets, and appear to contain some organic compounds, while the terrestrial planets do not.

The von Weizsäcker hypothesis, which appears to have considerable promise, may require some revision when it has been more completely explored. If this hypothesis is accepted, then we may conclude that the formation of a planetary system is the last stage in the formation of a star, and that this process has taken place in practically all of the stars.

What Can We Conclude?

The formulation of a hypothesis on the origin of the solar system brings us into the realm of speculative thought, but not of *a priori* reasoning, for there are many facts and principles with which the hypothesis must agree. The problem is no longer confined to the fields of astronomy and mathematics; in geochemistry, chemistry, and physics, there have been new developments which are pertinent. It is probable that about three billion years ago the solar system was in a different state from that at present, and that some great change must have taken place. The sudden catastrophic change assumed in the dualistic hypothesis failed to account for the distribution of angular momentum in the system unless three stars were in-

volved. The alleged condensation of the extremely hot gases drawn from the sun to form the planets could not have taken place.

The revival of the Kant-Laplace idea of a slower evolutionary development in a closed system (monistic) has stimulated a number of interesting and promising hypotheses based on recent developments in the physical sciences. The newer hypotheses or modifications of the older ideas have removed some of the former objections, but are based upon premises which are highly speculative and imaginative. Additional research and investigation in the related fields as that now conducted by ter Haar, by H. S. Brown, and many others may lead to confirmation, revision, or abandonment of the hypotheses now in vogue, and the formulation of new ideas.

But any hypothesis must explain all of the facts and be in harmony with all of the known principles before it can be advanced to the status of a theory. This will probably not occur, at least in the near future, for the birth of the solar system took place too long ago and on too colossal a scale for anyone to design a crucial experiment to test any of the hypotheses.

SUMMARY

1. Science is concerned with the origin of the solar system which, while speculative, involves a strict use of the scientific method.
2. The age of the earth is estimated by several methods:
   (*a*) The rate of deposit of sedimentary rocks.
   (*b*) The rate of erosion of the continents.
   (*c*) The quantity of salt in the oceans.
   (*d*) Retracing mathematically the motion of the moon to a position very close to the earth.
   (*e*) The rate of radioactive decay — the most accurate method. The age of the earth is thought to be somewhat over two thousand million years.
3. The properties and relevant facts of the solar system are:
   (*a*) Isolation in astronomical space.
   (*b*) Complexity, yet a regularity and organization.
   (*c*) All members, except some of the planetoids, lie in approximately the same plane, which is that of the sun's equator.
   (*d*) All the planets revolve in nearly circular orbits, and some of them rotate in this plane, all in the same direction, and at distances which are widely separated, but which are in accord with the Titus-Bode Law.
   (*e*) The satellites revolve in this same plane, but several move in a retrograde direction.
   (*f*) Most of the angular momentum of the system is possessed by the planets, which comprise less than one-seventh of one per cent of the total mass of the system.
   (*g*) The common elements which form the body of the earth constitute only about one per cent of the sun, which is composed mostly of hydrogen and helium. Great clouds of dust and gas of extremely low density exist in interstellar space.

4. Dualistic hypotheses initiated by Buffon and developed by Moulton and Chamberlin, Jeans and Jeffreys, Lyttleton and others assume a collision or near collision with another star or with the sun or companion star. They were abandoned when it was shown that a hot filament drawn from the sun would expand into a cloud rather than condense to form the planets.
5. Monistic hypotheses, initiated by Kant, all postulate the birth of the solar system from a great cloud of gas and dust particles.
   (*a*) According to the *nebular hypothesis* (Laplace) a rotating gaseous nebula shed rings of gas, each of which (with one exception) condensed and gathered together to form a planet. This hypothesis, long accepted, explains most of the properties of the system but does not account for the distribution of angular momentum, the formation of the planets from rings of gaseous material, and the retrograde motions of certain satellites.
   (*b*) Alfvén's theory assumes ionization of gas atoms drawn to the sun from a cloud and a subsequent ionization and a concentration of the ions in the region of the sun's magnetic equation followed by condensation.
   (*c*) The *dust-cloud hypothesis* (Whipple) starts with a cloud of gas and dust particles, the latter collecting under the influence of light pressure. The cloud contracted, slowly at first, but finally at a very rapid rate, to form the sun and the planets. The nuclear reactions taking place in the sun were initiated at the high temperatures reached in the contraction. The planets were formed in a stream in the cloud from great masses (protoplanets) which spiraled around the sun. The satellites were similarly formed from the outer cloud of material remaining around a planet. The original cloud did not rotate; the high angular momentum of the planets is the result of the spiral-like motion of the dust stream from which they were formed. The hypothesis explains most of the regularities and properties of the system except the Titus-Bode law. The initial formation of the nucleus in the rare dust gas cloud is not satisfactorily explained.
   (*d*) In the *von Weizsäcker hypothesis* it is assumed that the sun, formed by the condensation of interstellar matter, was enveloped by a cloud of gas and dust. In the cloud, which assumed a disc-like shape, viscous forces caused the inner parts to be decelerated and move toward the sun and the outer parts to be accelerated and move out into space, thus transferring angular momentum to the outer part of the system. The material escaping was of low atomic weight. The fine dust particles grew at first by collision and then by gravitational attraction. The motions of the particles became organized and the growth of the planets occurred at the junction of rings of vortices, spaced in a geometrical progression. The satellites were formed in a similar manner from dust clouds around the planets. The hypothesis removes some of the objections of the Kant-Laplace hypothesis and gives an explanation for the Titus-Bode law, the distribution of angular momentum, and the differences in chemical composition between the planets and the sun.

STUDY EXERCISES

1. Write a brief statement to show how each of the following methods used to estimate the age of the earth may be inadequate.
   (*a*) The rate of deposit of sedimentary rocks.
   (*b*) The rate of erosion of the continents.
   (*c*) The quantity of salt in the sea.
   (*d*) The gradual movement of the moon away from the earth as caused by tidal friction.

2. The chemical and isotopic content of rocks bearing naturally radioactive elements gives a more accurate method for measuring the age of the earth, for (check each correct statement):
   .... radioactive disintegration proceeds at a constant rate which is not influenced by conditions.
   .... radioactive decay could have begun only after the material which now comprises the earth had been drawn from the sun.
   .... radioactive decay dates not from the formation of the earth but from the time of formation of radioactive substances, whereas the permanent deposit of the end products in the same minerals probably dates from the solidification of the rock in which it is found.
   .... radioactive decay is continuous and suffers no interruptions, once started.

3. Prepare a list of facts or properties of the solar system
   (*a*) which may be regarded as a part of a regularity or organization.
   (*b*) which may be regarded as irregular or exceptional.

4. Assume that a tenth planet is discovered beyond Pluto. Assuming the Titus-Bode law holds, calculate its probable distance in astronomical units.

5. Assume that a body is completely isolated and is rotating. Check each of the statements below if correct.
   .... If the body shrinks but retains the same mass, it should rotate at the same rate.
   .... If the body shrinks it should rotate faster but retain the same quantity of angular momentum.
   .... If the body sheds a ring of dust and gas, the total angular momentum of the system remains constant.

6. Mark each statement as follows: *D*, if true only of the dualistic hypothesis; *M*, if true only of the monistic hypothesis; and *B*, if true of both.
   .... The sun in somewhat the same form as at present was the parent body.
   .... The sun was either quite different from its present state or was formed from a nebula as the first major step in the evolution of the solar system.
   .... The earth was originally gaseous and hot.
   .... The system was always isolated and with a constant angular momentum.
   .... The present distribution of angular momentum in the system was the result of a close encounter or collision of the sun with another star.
   .... The nearly circular orbits of the planets were due to constant impacts with other bodies.

7. Discuss briefly the main reason why the dualistic hypotheses were recently abandoned.

8. Mark *A*, if true only of the nebular hypothesis; *B*, if true only of the von Weizsäcker hypothesis; *C*, if true only of the dust-cloud hypothesis; and *D* if true of all three:
   .... The solar system originated from a nebula.
   .... The planets were formed from gaseous rings shed by the rotating nebula.
   .... The planets were formed from a dust stream in the dust-gas cloud.
   .... The planets were formed by accretion from the dust particles along the rings of vortices.
   .... The distribution of angular momentum is explained by the loss into space of the material which had most of the angular momentum and the acquisition by the sun of the material for which this value was zero.
   .... The distribution of angular momentum is explained by the assumption that the original whole nebula had no rotary motion and the motion of the planets was due to the spiral-like motion of the dust stream from which they were formed.
   .... The explanation for the distribution of angular momentum was not satisfactory and contributed to the abandonment of the hypothesis.
   .... Utilizes the idea of light or radiation pressure.
   .... Explains most satisfactorily the Titus-Bode law.

9. Write a short essay in which you show how the world was prepared for the reception of the nebular hypothesis, and what great influence it exerted on thought for over one hundred years.

10. Discuss the possibilities for the development of an hypothesis on the origin of the solar system which might ultimately become a theory.

FOR FURTHER READING

1. Whipple, F. L., *Earth, Moon and Planets.*
   Chapter 14 contains a brief treatment of the older theories of the origin of the solar system including a mention of Lyttleton's double-star hypothesis. Good for an introductory study.

2. Moulton, F. R., *Astronomy.*
   In Chapter 14 is a well-written account of the evolution of the solar system by one of the authors of the planetesimal hypothesis.

3. Jeans, J. H., *The Universe Around Us.*
   Chapter 4 includes a much broader discussion of the birth of nebulae, stars, binary systems, and finally the solar system. The author ably presents his tidal hypothesis.

4. Russell, Henry Norris, *The Solar System and Its Origin.* New York: The Macmillan Company, 1935.
   In this interesting little book the author discusses the dynamical properties of the solar system, its chemical and physical properties, and the various older theories of its origin.

5. Wolf, A., *A History of Science, Technology, and Philosophy in the Eighteenth Century.* New York: The Macmillan Company, 1939.

Historical treatment of astronomy in the eighteenth century including the speculations of Kant and the nebular hypothesis. Both volumes of this excellent work contain well-illustrated chapters on astronomical instruments during the sixteenth, seventeenth, and eighteenth centuries. See especially Chapter 4.

6. Duncan, J. C., *Astronomy.*

Chapter 14 contains discussion of older theories.

7. Gamow, George, *One Two Three . . . Infinity.* New York: The Viking Press, 1947.

In Chapter 11 a brief review of some of the older theories and a more detailed description of the von Weizsäcker hypothesis is given.

8. Whipple, F. L., "The Dust Cloud Hypothesis," *Scientific American* (May, 1948), page 35.

A detailed, well-illustrated presentation of this recent hypothesis by its author.

9. Page, Thornton L., "The Origin of the Earth," *Physics Today* (October, 1948), page 12.

A critical review of the various hypotheses on cosmogony.

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Inquiries into the Past

IN THE PRECEDING CHAPTER we learned of evidence justifying the conclusion that the age of the earth is at least two billion years. It is impossible not to be curious about the events that have occurred during that long interval. The science concerned with the study of the past history of the earth is *historical geology*. In Chapters 6 to 10, a study was made of the various geological processes — gradation, diastrophism, and volcanism — which continually modify the contour and appearance of the earth's surface. When students of earth science realized that there were numerous evidences of the operation of past geological processes buried deep in the earth's rocky crust, it became necessary to modify the orthodox conception of the past history of the earth as recorded in the pages of written — and especially of Biblical history. During the seventeenth century the Biblical chronology of Bishop Usher represented a great triumph of critical historical research. According to this chronology, the events recorded in the Book of Genesis occurred in 4004 B.C. To the scholar of the Middle Ages all the events of past time had happened within a span of six thousand years. But man was later presented with evidence from many sources that compelled an upward revision of this figure, not once but many times. Some of the answers to the age-old questions "From whence came our earth, how was it fashioned, and what is its age?" came slowly. The answers were found written in stone, sealed within the crust of the earth.

The founder of historical geology was a Scotch scientist, James Hutton, who died in 1797. He pointed out that granite was igneous rock that had migrated from the earth's interior into surface rocks. He showed that unconformities were former erosional surfaces that had been hidden by later sediments, and that the sediments above the unconformity were therefore younger than the rocks underneath. He correctly attributed the presence of marine fossils in mountain ranges to the elevation of rocks formed from sediments once deposited on the bottom of former seas. Before Hutton's time the surface features of the earth, its mountains, valleys, lakes, and rivers, were considered to have always existed in their present

forms. Hutton pointed out that they are but transitory features due to the various processes of erosion, diastrophism, and volcanism.

Our knowledge of the earth's past history was uncertain and contradictory as long as scientists depended for information on the records of events left by man. But when geologists came to recognize fully the significance of Hutton's ideas they realized that they had found a Rosetta Stone to enable them to read history from the earth's rocky crust. The deciphering key consists of a series of six broad general principles which are the foundations of historical geology. It is possible to apply these principles because the rocks reveal that the earth is always in the process of change. Our knowledge of the past history of the earth would be negligible in comparison with what we now have if the earth were a static, unchanging body. The man who first wrote about the "everlasting hills" was really exercising poetic license, not telling scientific truth. The "everlasting hills" truly are ever-changing hills. The keynote to geological history is change — steady, ceaseless change.

Basic Principles of Geological History

1. *Seas Inundate the Land.* Large portions of the present continents have often been alternately above and below sea level. This may be due either to an actual change in the level of the land surface with respect to the oceans, or to a variation in the amount of water in the oceans great enough to change appreciably the amount of exposed land surface. The interior of much of the North American continent has been alternately above and below sea level many times. In the lower part of the United States a depression of the land levels of only two hundred and fifty feet would again bring the Gulf of Mexico as far north as St. Louis. During the many periods of inundation the present sedimentary rocks were deposited.

One of the most interesting illustrations of the advance and retreat of a sea due to a change in land level is provided by the ancient Roman temple of Jupiter Serapis on the coast near Naples, Italy. In 1749, the upper parts of three standing marble columns were discovered. When excavated, the site revealed a structure which, judging from inscriptions, must have been above the sea as late as A.D. 235. The lower part of the temple had been buried in typical marine sediments to a depth of twelve feet. Furthermore, various borings on the columns made by marine animals indicated that the temple had once been submerged to a depth of twenty-one feet. Subsequent to A.D. 235, then, the whole region had gradually subsided until the temple was immersed to a depth of twenty-one feet, and then the region began to rise again. The elevation of the region had continued until in 1828 the temple was a hundred feet from the sea.

2. *The Law of Uniformitarianism.* This is the formal way of referring to the important generalization of James Hutton. The law may be summed up as follows: The geological forces that operated to modify the

earth in the past are the forces that are modifying the earth at the present time by weathering, erosion by streams, ice, shore agencies, and action of ground water, diastrophism, and volcanism. The presence of ripple marks on sandstones high in a mountain range is evidence enough that the stone was once loose sand driven by the wind or waves, perhaps on the shore of a former ocean. The presence of ancient animal tracks in hard shale proves that this rock was part of an ancient mud flat. Glaciers today, as they move down their mountain valleys, scratch and polish the rock surfaces. The presence of glacial scratches and polish on exposed surface rocks anywhere in the northern part of our country proves that this region was once buried beneath an ancient ice sheet.

3. *The Law of Superposition.* One of the most important geological processes, weathering and erosion (degradation), is continually reducing in elevation the higher portions of the earth's crust. Much of the eroded material finds its way through the agency of streams into lakes and oceans. In these relatively quiet waters the material in suspension settles out to form sediments which in the course of geological time form sedimentary rocks. Hence the oceans over three-fourths of the earth's surface are serving as graveyards for the other fourth. Over wide intervals of time, therefore, many layers and kinds of sedimentary rocks will be laid down one above the other. It follows, then, that the youngest rocks are at the top and the oldest are at the bottom. This generalization is usually referred to as the *Law of Superposition.*

4. *The Law of Unconformity.* In Chapter 9, evidence was presented for the first principle just discussed, namely, that the crust of the earth in some regions has oscillated above and below sea level many times. When the region was submerged, series of sedimentary rocks were formed. When the region was elevated, the upper rocks were eroded away. If this region was then resubmerged, the formation of sedimentary rocks would again occur on the former erosion surface. If the region was again elevated, renewed erosion would eventually reveal an *erosional unconformity.* If the rocks above the unconformity are essentially parallel to the rocks below the unconformity, it may be difficult to detect. The geologist must then exercise considerable ingenuity in acquiring and interpreting the facts which will lead to a definite recognition of an unconformity. For example, if the lower rocks contain fossil remains of a form of life that lived two hundred million years ago, whereas the upper rocks contain fossils that were alive only sixty million years ago, the surface of separation must be an unconformity, or more properly, a *disconformity.* Usually, however, in the movements of the earth's crust there is a certain amount of folding or tilting, so that the location of the ancient erosional surface beneath the younger sedimentary rocks is easily discerned. Where one layer of rocks forms an angle with the layers of a later series, the line of separation is called an *angular unconformity.* (Refer to Figure 126.) The significant thing

about erosional unconformities is that they reveal a lost time interval, where the rock record is incomplete. The methods used by the geologist to get a measure of this lost time interval will be discussed later.

5. *The Law of Intrusion.* There are many places where sedimentary rocks have been penetrated by igneous magma from the earth's interior to form dikes, sills, and laccoliths. Which event is the antecedent event — the formation of the sedimentary rocks or the period of igneous activity? Of course, there can be only one answer: the igneous rock flows must always be younger in age than any series of rocks they may penetrate. This is the *Law of Intrusion.*

6. *The Law of Organic Correlation.* Rocks which contain the same kind of fossils, so-called index fossils (see below), are of similar age. Sedimentary rocks almost invariably contain various fossils. Just when life appeared on this earth is unknown, but the fossil forms from the oldest rocks are from very simple forms of life. It is reasonable to believe that the first forms of life were one-celled forms without hard parts, a condition not conducive to their preservation. With the passage of time, more complex forms of life evolved in the waters of the seas. For example, some of the oldest exposed sedimentary rocks on the North American continent are found near the bottom of the Grand Canyon in Arizona. In these rocks are found remains of lime-secreting algae which represent a very low type of life. Farther up the canyon wall are found rocks containing the remains of sea weeds, various kinds of shells and corals, and invertebrate sea animals. In still younger rocks nearer the rim of the canyon, there are found remains of fernlike plants and insects, and tracks of primitive reptiles and amphibians. Thus, at progressively higher and higher levels can be found evidence of increasingly complex forms of animal and plant life. The biological scientist uses fossils as evidences for the doctrine of the evolution of life. The geologist uses them as dates in his calendar of time: Limestone in the region of Chicago which contains fossils identical with the limestone exposed at Niagara Falls, he argues, must have been formed at the same time in the geological calendar. The principle which states that rocks which contain similar fossils must be of the same age, even though widely separated geographically, is known as the *Law of Organic Correlation.*

The Geological Time-Table

Utilizing these six laws, geologists during the past hundred years have entirely reconstructed our conception of the past history of the earth. Here is an inspiring example of how the sum total of human knowledge grows slowly by the co-operative efforts of many workers in many countries and in more than one line of endeavor. We are indeed debtors to the past. One of the unsolved problems of science a hundred years ago, for example, was to account for the nature of the mantle soil (gravel, cobbles,

Table 68. Geological Time Chart

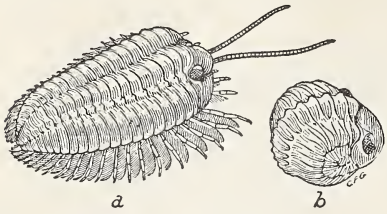
Eras	Part of Geological Time	Periods	Duration in Years*	Years from Present	Dominant Life	Closed with
Cenozoic	$\frac{1}{30}$	Recent [1]	10,000		Man	
		Pleistocene [1]	2,000,000			Cascadian Revolution
		Pliocene [2]	10,000,000		Mammals	
		Miocene [2]	18,000,000			
		Oligocene [2]	10,000,000			
		Eocene [2]	20,000,000	60,000,000		
Mesozoic	$\frac{1}{14}$	Cretaceous	70,000,000		Flowering plants, grasses Reptiles	Laramide Rocky Mountain Revolution
		Jurassic	38,000,000			
		Triassic	32,000,000	200,000,000		
Paleozoic	$\frac{1}{6}$	Permian	35,000,000		Amphibians	Appalachian Revolution
		Carboniferous[3]	80,000,000			
		Devonian	35,000,000		First plant life Fishes	
		Silurian	25,000,000			
		Ordovician	70,000,000		Invertebrates	
		Cambrian	105,000,000	550,000,000		
Proterozoic	$\frac{1}{3}$	Upper Pre-Cambrian	650,000,000	1,200,000,000	Primitive multicellular forms	Killarney Grand Canyon Revolution
Archeozoic	$\frac{2}{5}$	Lower Pre-Cambrian	800,000,000	2,000,000,000	Unicellular forms possible	Laurentian Revolution
Azoic	Interval from birth of sun to formation of earliest sedimentary rocks.		1,000,000,000 (?)		No Life	

* After Croneis and Krumbein, *Down to Earth* (University of Chicago Press), pages 298–299.
[1] Also called the Quaternary Period.
[2] Also called the Tertiary Period.
[3] Often divided into Pennsylvanian and Mississippian Periods.

and boulders) over a large portion of the northern hemisphere. These superficial deposits had no relation whatever to the rock on which they were deposited. In 1840, Louis Agassiz, a botanist, published a momentous work, *Studies on Glaciers*, in which he applied James Hutton's law of uniformitarianism to prove that the deposits of débris soil over the northern part of the continents were glacial in origin — deposits left by a former ice sheet which moved southward over Europe, Asia, and North America during the Pleistocene Period of the Cenozoic Era. All through this glaciated area could be found exactly the same kind of scratchings and deposits as were left by the small valley glaciers in the Alps This is but one illustration of how geologists have gradually reconstructed the historical record of the earth, divided into five great geological volumes, or eras, and these eras into about fifteen smaller chapters called periods. Eras are based upon the state of advancement (evolution) of plants and animals: Archeozoic (primitive life), Proterozoic (early life), Paleozoic (ancient life), Mesozoic (medieval life), Cenozoic (recent life). These divisions result from the correlations of rocks from the entire continent by studies in composition, manner of occurrence, and kinds of fossils present. (See Table 68.) The importance of the table lies in the fact that it gives in very broad outlines the major events in the development of the North American continent — as the result of diastrophism or mountain-building, and in the development of life during geological time. The five great divisions of time are based upon the events recorded in the last two columns.

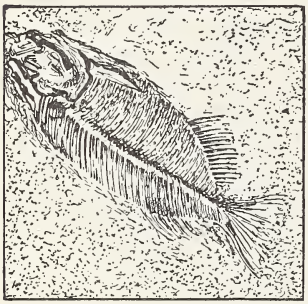
Index Fossils

The term fossil is applied to any remains or evidences of former life. Fossils may be actual remains, whether unaltered or altered; casts or molds, such as imprints of leaves, of bony structures, and tracks of animals and birds; or artificial structures made by animals or primitive man. Only rarely are unaltered plant and animal remains found. On a few occasions, for example, complete mammoth (prehistoric elephant) carcasses have been found frozen in the ice or the tundras of northern Siberia after being in cold storage for perhaps twenty-five thousand years. Usually fossils are found in sedimentary rocks, and they have been buried so long that none of the original plant or animal survives except as a cast or mold, or as altered remains. The conditions favorable to fossil formation are the presence of hard parts and quick and deep burial. This means that the material is protected from the action of air under conditions which favor preservation. Then the soft and hard parts of organisms are slowly replaced by calcium carbonate (*calcification*) or silicon dioxide (*silicification*) from the materials dissolved in the ground water, a process called *petrification*. Occasionally, the organic matter in buried plant and animal life decays in such a way as to leave only carbon. The fossil remains of an



(A) Trilobite of Silurian Time — Calymene Niagarensis.
(*a*) extended; (*b*) coiled. (*Courtesy of Field Museum*)

(B) Dinosaur of Jurassic Time — Brontosaurus excelsus. This fossil has a length of 67 feet.



(C) Early Cenozoic fish of Eocene Period

(D) Ancient fern of Late Paleozoic (Carboniferous)

FIGURE 450. EXAMPLES OF INDEX FOSSILS

ancient fish shown in Figure 450 (C) consist of carbon from the original flesh about the bony skeleton. This process is called *carbonization.*

Rock strata of different ages contain fossils so characteristic that they can be used as guide or index fossils to correlate rocks of a given age from place to place or from continent to continent. (Refer to Figure 450.) To be useful as index fossils, they should possess certain characteristics:

1. They should have wide geographical distribution, in order to correlate rock strata over entire continents or from continent to continent.
2. They should be very abundant and easy to identify.
3. They should be distributed over a narrow time interval; that is, a form of life that persisted over too great a time interval — over two or more geological eras — could not be used to place a particular stratum of rock into its proper niche in the geological time-table.

The Divisions of Geological Time

It is natural to inquire about the basis for the division of geological time into five eras, and the subdivision of the eras into periods. The answer is that these correspond to natural breaks in the story of the earth's history caused by diastrophic disturbances resulting from widespread adjustments in the earth's crust. These adjustments, as we have seen, resulted in alternate elevation and resubmergence of large areas of all the continents and the formation of large mountain systems. For example, various parts of the North American continent have been flooded by the seas at least twenty times. These widespread crustal movements often brought about profound changes in climate which caused many land-forms of life either to disappear or to evolve into other forms which could survive in the new environmental conditions. Such widespread continental disturbances are called *geological revolutions.*

From the time of the Greek philosophers, scientists have been puzzled by the widespread continental distribution of many different forms of marine shells, often at an elevation of thousands of feet above any present seas. The answer to the puzzle was simple, but it did not come until the clear recognition of the first basic truth of geological history stated above on page 851. We now know, for example, that the eastern coast of the United States has recently settled, geologically speaking, allowing the Atlantic Ocean to flood the low coast lands. This accounts for the many drowned valleys surrounding the Chesapeake Bay, for instance. The annual rate of rising or falling of a portion of continent may be difficult to detect, but geological time must be reckoned not only in millions of years, but in tens and hundreds of millions of years. A change in elevation of one centimeter a year would be difficult to detect, but during a normal lifetime it would equal about two feet. This rate, if continued for a million years, would form mountains higher than the present Himalayas.

The Cycle Illustrated in the Paleozoic Era. The cycle of submergence, emergence, and mountain-building characteristic of a geological era can be illustrated by what happened in our own continent during the Paleozoic Era. In the early part of the era, the North American continent began to be submerged. There is evidence to indicate that the degree of submergence increased with time until a very large part of the continent was under water, as indicated in Figure 451. There were three distinct regions of uplands: Appalachia, Cascadia, and the Canadian Shield. The Canadian Shield represented the remnants of the Laurentian Mountains, which had been largely eroded away during the Proterozoic Era. During a part of this early period, the Killarney Mountains of Wisconsin, which had been built at the close of the Proterozoic Era, were still conspicuous in the interior of the continent.

Thanks to the abundance of water and a mild climate, the forces of gra-

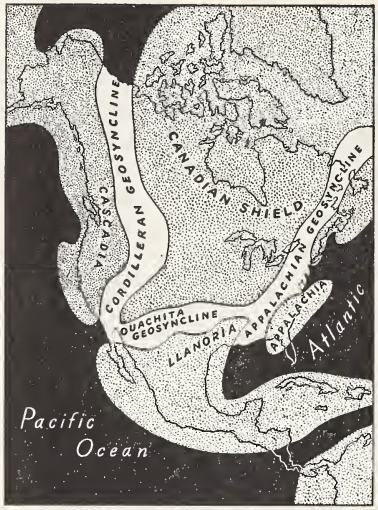


FIGURE 451. APPEARANCE OF NORTH AMERICAN CONTINENT DURING THE EARLY PART OF PALEOZOIC ERA — CAMBRIAN

(Adapted by permission from "Outlines of Historical Geology," by C. Schuchert and C. O. Dunbar, published by John Wiley and Sons, Inc.)

dation operated rapidly, and the eroded materials from the highlands were deposited into three great troughs called *geosynclines*: the Appalachian, the Cordilleran, and the Ouachita. A cross-section through the present central United States would appear as shown in Figure 452. These geosynclines caught all the débris eroded from the adjacent highlands, until in some places the deposits of the resulting sedimentary rocks were as thick as fifty thousand feet.

During the latter part of the Paleozoic Era, diastrophic disturbances occurred on a wide scale which resulted in shortening the earth's surface in the eastern part of the present United States about a hundred miles. Those forces pushed the remnants of the old Appalachian Highlands westward, crushing and folding the sedimentary rocks in the Appalachian geosyncline into a mountain chain that extended from the present Nova Scotia to Alabama — the new Appalachian Mountains. Contemporaneous with this uplift there was a minor disturbance that produced uplands in southern Arkansas and southeastern Oklahoma now called the Ouachita Mountains. (Refer to Figure 454.)

North America in the Mesozoic Era. This same cycle or sequence is admirably illustrated also by the Mesozoic Era, during which the eastern half of our continent was emergent with forces of erosion in operation. Gradually a huge geosyncline in the general region of the former Cordilleran trough came into existence, and it continued to increase until it

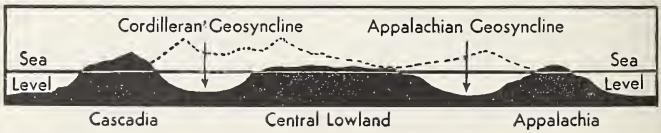
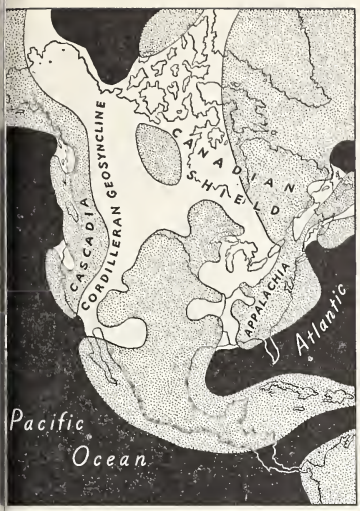
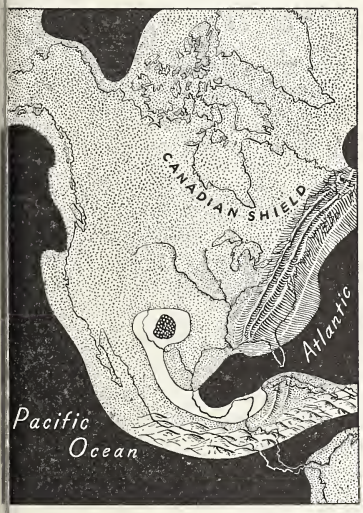


FIGURE 452. A CROSS-SECTION THROUGH THE PRESENT UNITED STATES DURING THE EARLY PALEOZOIC ERA



IGURE 453. APPEARANCE OF NORTH
MERICA IN MIDDLE SILURIAN TIME
F PALEOZOIC ERA

FIGURE 454. NORTH AMERICA DURING CARBONIFEROUS PERIOD



IGURE 455. APPEARANCE OF NORTH
MERICA AT CLOSE OF PALEOZOIC
RA. THE CONTINENT WAS LARGELY
MERGENT

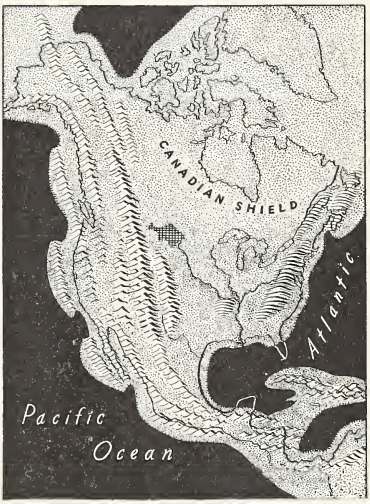


FIGURE 456. APPEARANCE OF NORTH AMERICA AT THE CLOSE OF THE MESOZOIC ERA

(*Adapted by permission from "Outlines of Historical Geology," by C. Schuchert and C. O. Dunbar, published* John Wiley and Sons, Inc.)

reached its climax during the Cretaceous Period. Into this trough was poured the débris that later was to form the present Rocky Mountains. The North American continent was divided into two distinct land masses by the seas in the Rocky Mountain geosyncline. In various parts of Wyoming, Colorado, and Utah — which during the Mesozoic Era formed the western shore of the sea in the Rocky Mountain geosyncline — we have a rich source of fossil remains of dinosaurs, one of the most characteristic forms of life in the Mesozoic Era. After an existence long enough to accumulate sediments many thousands of feet thick, compressional forces came from the west which eventually elevated the deposits in the geosyncline to create the first generation Rocky Mountains. This is designated as the *Laramide Revolution.* Again a great mountain-making cycle had been repeated: (1) submergence (epeirogeny), (2) simultaneous erosion and sedimentation, and (3) mountain-building. (See Figure 456.)

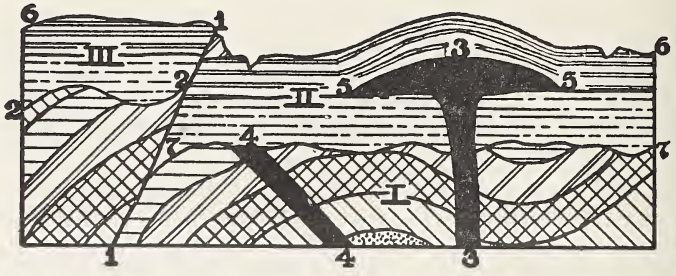
To sum up, then, a geological era is a major division of geological time marked off by extensive emergence of parts of continents submerged during the early part of the era. These widespread movements of land masses which result in the raising and lowering of large areas are called epeirogenic movements. The eroded materials are carried to huge troughs called geosynclines. This redistribution of material results in the accumulation of strains on a large scale, which, when they become sufficiently great, result in a geological revolution, the latter being always marked by orogenic movements, or mountain-building, a final process which closes a geological era. New characteristic forms of life often followed geological revolutions as a result of rapid evolutionary changes due to changed environmental conditions.

Geological Periods. During every geological era there were regions where submergence and emergence occurred on a much smaller scale which nevertheless resulted in definite transformations in the appearance of the continent. These changes, confined to regions within a continent, are called geological periods. For example, in the Middle Paleozoic Era (Figure 453) a region in the east central part of the United States was submerged, and during this period the Niagara limestone, exposed at Niagara Falls and in many places in Ohio, Indiana, Illinois, Wisconsin, and Michigan, was laid down. The Middle Paleozoic time, divided into Silurian and Devonian Periods, was terminated with the formation of the Acadian Mountains in New England and eastern Canada. Again, during the latter part of the Paleozoic Era, a region stretching from Pennsylvania to Texas fluctuated above and below sea level many times. This alternately formed a vast shallow sea and swampy lowlands (see Figure 454). The climate at this time was very humid and mild and supported extremely dense vegetation. This formed deposits of organic matter, which, when later buried and subjected to the forces of compaction, formed our great coal deposits. This period of time has been labeled the *Carboniferous Period,*

and it is divided into the Mississippian and Pennsylvanian. The most important coal-producing regions are distributed in rocks of the Pennsylvanian period along an arc running from Texas, through Oklahoma, Kansas, Missouri, Iowa, Illinois, Kentucky, Indiana, Ohio, West Virginia, and Pennsylvania. These coal regions are the result of changes occurring during a geological period.

SUMMARY

1. It is possible to reconstruct the past history of the earth because the rocks reveal many evidences of a continuous process of change in the condition of the earth's surface during past geological time.
2. The basic facts and principles used by the geologist to interpret the significance of the changes in the condition of the earth during geological time as revealed by studies of the earth's crust are as follows:
   (*a*) Large portions of the present continents have been alternately above and below sea level.
   (*b*) The geological processes that have operated in the past are the processes that are now in operation, including gradation, diastrophism, and volcanism — the Law of Uniformitarianism.
   (*c*) In a conformable series of sedimentary rocks, the youngest rocks are on top and the oldest rocks on the bottom — the Law of Superposition.
   (*d*) The presence of an unconformity indicates a break in the rock record, since the lower layer of rocks were deposited, uplifted, and eroded away before the upper series were deposited — the Law of Unconformity.
   (*e*) Igneous rocks are younger than the sedimentary rocks into which they have penetrated — the Law of Intrusion.
   (*f*) Rocks which contain the same index fossils are of similar age — the Law of Organic Correlation.
3. Fossils which evolved and disappeared during a relatively short period of time and which can be used to correlate the rocks of one region with those of another are called index fossils.
4. Index fossils should have the following characteristics:
   (*a*) They should be very abundant and easy to identify.
   (*b*) They should have existed over a narrow time interval.
   (*c*) They should have wide geographical distribution.
5. Geological time has been divided into five great eras, each subdivided into periods. The student should familiarize himself with the names, length in terms of fraction of geological years, dominant forms of life, and the events which closed each era, as given in Table 68.
6. Each geological period is characterized, first, by widespread crustal movements (epeirogeny) which elevate and also submerge large parts of the continents; second, the formation of great geosynclines; third, a long period of erosion of the exposed portions of the continents which produced thick sediments in the geosynclines; fourth, the evolution of characteristic forms of life; and fifth, an accumulation of great strains within the earth's crust which



are eventually relieved by mountain building (orogeny) in the regions of the great geosynclines.

7. The extensive periods of orogeny which mark the close of each era are called geological revolutions.
8. Minor changes over a smaller area of the continents, similar to those characteristic of a geological era and completed in relatively short intervals of time, divide the eras into periods.

STUDY EXERCISES

1. The following exercises refer to the diagram above. In each exercise underline the *one* alternative in parentheses that correctly completes the statement:
   (*a*) There is evidence of (*A*, no; *B*, one; *C*, two, *D*, three; *E*, four) main period(s) of sedimentation.
   (*b*) There is evidence of (*A*, no; *B*, one; *C*, two; *D*, three; *E*, four) period(s) of diastrophism.
   (*c*) There is evidence of (*A*, no; *B*, one; *C*, two; *D*, three; *E*, four) period(s) of volcanism.
   (*d*) There is evidence of (*A*, no; *B*, one; *C*, two; *D*, three; *E*, four) main period(s) of erosion.
   (*e*) There is a thrust fault at (*A*, 1-1; *B*, 2-2 and 7-7; *C*, 3-3 and 5-5; *D*, 4-4; *E*, no location).
   (*f*) There is a tension fault at (*A*, 1-1; *B*, 2-2 and 7-7; *C*, 3-3; *D*, 4-4; *E*, no location).
   (*g*) There is an unconformity at (*A*, 1-1; *B*, 2-2 and 7-7; *C*, 4-4; *D*, 6-6; *E*, no location).
   (*h*) There are dikes at (*A*, 1-1 and 7-7; *B*, 2-2 and 7-7; *C*, 3-3 and 4-4; *D*, 5-5 and 6-6; *E*, no location).
   (*i*) There is a sill at (*A*, 1-1; *B*, 2-2 and 7-7; *C*, 4-4; *D*, 5-5; *E*, no location).
   (*j*) There is a batholith at (*A*, 1-1; *B*, 2-2 and 7-7; *C*, 3-3 and 5-5; *D*, 4-4; *E*, no location).
   (*k*) There is a laccolith at (*A*, 1-1; *B*, 2-2 and 7-7; *C*, 3-3 and 4-4; *D*, 5-5; *E*, no location).
   (*l*) There is evidence of a long period of erosion at (*A*, 1-1; *B*, 2-2 and 7-7; *C*, 4-4; *D*, 6-6; *E*, no location).

(*m*) There is evidence of a relatively short period of erosion at (*A*, 1-1; *B*, 2-2 and 7-7; *C*, 4-4; *D*, 6-6; *E*, no location).
(*n*) There is evidence of a period of mountain-building at (*A*, I; *B*, III; *C*, 1-1; *D*, 4-4; *E*, no location).
(*o*) The rocks at III are most likely to be (*A*, granite; *B*, basalt; *C*, marble; *D*, schist-like; *E*, sandstone).
(*p*) The rocks at I are most likely to be (*A*, granite; *B*, basalt; *C*, limestone; *D*, schist-like; *E*, sandstone).
(*q*) The rocks in 3-3 are most likely to be (*A*, granite; *B*, gneiss; *C*, limestone; *D*, schist; *E*, shale).
(*r*) Recognizable fossils are most likely to be found in (*A*, I; *B*, III; *C*, 3-3; *D*, 4-4; *E*, no location).
(*s*) The earliest event among the following is the formation of (*A*, 1-1; *B*, 2-2; *C*, 3-3; *D*, 4-4; *E*, 6-6).
(*t*) The structure 7-7 was formed after the formation of (*A*, 1-1; *B*, 3-3; *C*, 4-4; *D*, 5-5; *E*, 6-6).

2. In the space before each statement below write the letter —
A if the statement applies to the principle of intrusion.
B if the statement applies to the principle of uniformitarianism.
C if the statement applies to the principle of organic correlation.
D if the statement applies to the principle of superposition.
E if the statement applies to the law of unconformity.
.... Certain kinds of fossil plants and animals are characteristic of a formation of a given geologic age. Widely separated formations containing the same kind of fossils are therefore of the same geological age.
.... A lost interval is indicated when it is evident that a series of rocks was deposited, uplifted, eroded, and then covered by the deposition of a new series.
.... In a series of rock formations, the younger rocks are at the top and the older ones at the bottom, unless the former have been transposed by some violent disturbance.
.... Intrusive rock is younger than that which is intruded.
.... The processes of gradation, volcanism, and diastrophism, with which we are familiar today, have been in operation throughout geological history in essentially the same form; and from the evident results of these processes we can interpret the history of the earth.

3. Check those characteristics listed below which are true of index fossils:
.... are very abundant.
.... persisted without appreciable change through several geologic eras.
.... have a wide geographical distribution.
.... have a restricted geographical distribution.
.... have a limited geological distribution.
.... are easily identified.

FOR FURTHER READING

1. Croneis, C., and W. C. Krumbein, *Down to Earth.*
The history of the earth by masters of earth science. Chapters 24, 25, 26, and 27 discuss the methods used by the geologist to unravel the past history of the earth.

2. Schuchert, Charles, and C. O. Dunbar, *Outlines of Historical Geology*. New York: John Wiley and Sons, 1941.
Chapters 1, 2, 3, and 4 discuss with many illustrations the keys used by the geologist to unlock the record of the earth's past history.

3. "Geology," *Encyclopaedia Britannica*, 14th edition.
The following readings are recommended: The Geological Cycle, Stratigraphical Geology, and Paleontology.

4. Schuchert, Charles, and Clara M. LeVene, *The Earth and Its Rhythms*. New York: D. Appleton-Century Company, 1933.
The story of geology for the layman. Chapters IX, XIII, XV, XX, and XXI are concerned with the principles used in historical geology.

49

The Five Volumes of Geological History

AS POINTED OUT in Chapter 47, the most reliable method for determining the age of the earth depends upon the analysis of rocks which contain radioactive uranium. This method indicates an age of about two billion years. Strictly speaking, the earth must be older, since the above figure merely indicates that certain uranium minerals of that age have been found in rocks comparatively close to the surface. The scientist has no evidence whatever concerning the age of the rocks in the earth's interior. Preceding the earliest geological era, the Archeozoic, there was a period of which we know very little and which may have lasted a billion years or more. This is sometimes called the Azoic Era — the era without life in any form. We can surmise that this represents a time for cooling of the primordial earth. Not until an atmosphere had accumulated and cooling had occurred sufficiently to form the oceans did the process of gradation begin to operate. This was soon followed by the continuous process of buckling in the earth's crust (epeirogeny and orogeny) which produced the great geosynclines and the geological revolutions which mark off the five geological eras referred to in Table 68. For convenience this broad span of years is often divided into two sequences, the pre-Cambrian and that which followed the beginning of the Cambrian Period at the opening of the Paleozoic Era. The pre-Cambrian, in terms of years, represents nearly three-fourths of geological time, or about 1,450,000,000 years. The remaining fourth of geological time distributed over three geological eras, for which the record is relatively much more complete, corresponds then to about 550,000,000 years. The meagerness of the record for all of pre-Cambrian time is due, first, to the difficulty of studying the rocks belonging to these eras, since they are usually buried deep within the earth's crust, and second, to an almost complete absence of fossils. This means that the tasks of correlating rocks must be done without the help of index fossils.

The Grand Canyon Region

Geologically speaking, the Grand Canyon of the Colorado River, in Arizona, is one of the most interesting regions on the entire earth, for here

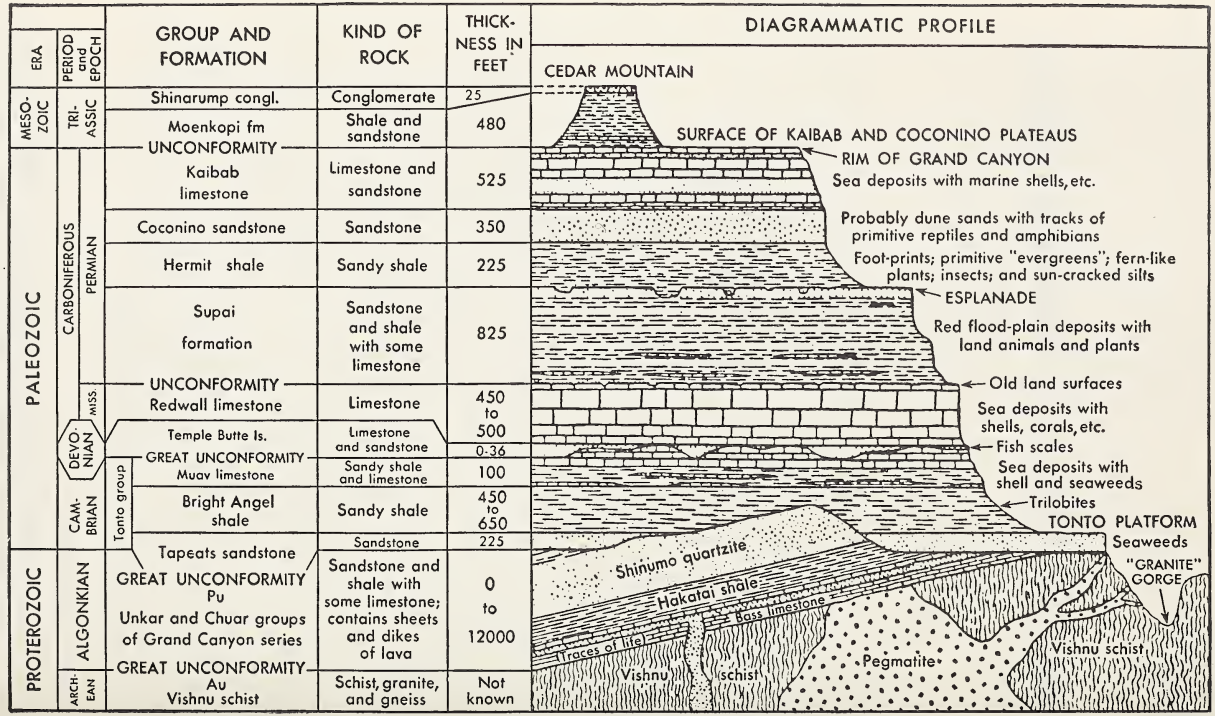


FIGURE 457. THE ROCKS IN THE GRAND CANYON

This is the north wall looking east. The Colorado River here runs east-west (after L. F. Noble).

rocks formed during the long interval from the Archeozoic to Mesozoic Eras, inclusively, can be studied in relation to each other in a single locality. The canyon is a young V-shaped valley, and the process of down-cutting is still rapidly going on. In places the canyon is about six thousand feet in depth, and it varies in width from five to fifteen miles. Most of the rock walls are sedimentary rocks, but at the bottom the river has cut a channel one thousand feet into metamorphosed rocks of the Archeozoic Era. These rocks are of great interest, because they are among the oldest readily accessible on the face of the earth. There is no doubt that these rocks were originally deposited as fine mud beneath an ancient sea, but after consolidation into shale they were subjected to enormous pressures and heat to form a schist — the Vishnu schist. (Refer to Figures 457 and 459.) The enormous pressures were due to the great weight of the overlying rocks when the Archeozoic and later landscapes emerged from the sea. This conclusion is supported by the fact that there are granitic intrusions into the Vishnu schist. Recall that in Chapter 7 it was pointed out that coarse-grained igneous rocks are formed only by slow cooling at considerable depth below the earth's surface. Metamorphism was also helped by the period of intense diastrophic movements that occurred in this region during the latter part of the Proterozoic Era (see below).

The evidence of a great erosional period in this region is indicated by the very distinct unconformity which marks the upper boundary of the Vishnu schist. (Refer to Figure 459.) This unconformity is indicated in Figures 457 and 458. The Vishnu schist (*V*) is immediately below this unconformity. The rocks immediately above the *Au* surface in Figure 458 are sedimentary rocks, though now inclined at an angle, such as the Bass limestone *B*, and the Hakatae shale *H*. It is here that there are to be found the first evidences of life. These rocks were deposited during a period of submergence when this whole region, undoubtedly, was an extension of the present Pacific Ocean. Interestingly enough, the rocks belonging to the second geological era are exposed only in the north wall of the canyon. Not a trace of them can be seen along the south wall. In fact, the unconformity at the bottom of the canyon in the south wall marks a lost time gap of many millions of years, since the superincumbent rocks are Paleozoic in age. These Proterozoic rocks when deposited were horizontal. But at the close of the era this region had a second emergence and was uplifted many thousands of feet above the sea. The uplift was unusually violent, as indicated by the many faults that have been discovered in the Proterozoic rocks. (Refer to Figures 458 and 459.) In some places, the displacement of rock along the faults amounts to hundreds of feet. But with the passage of time, degradational forces again leveled this whole region to a second prominent erosional surface. (This is labeled *Pu* in Figure 458. Also refer to Figures 457 and 459.)

Just above the *Pu* unconformity are many thousands of feet of Paleozoic

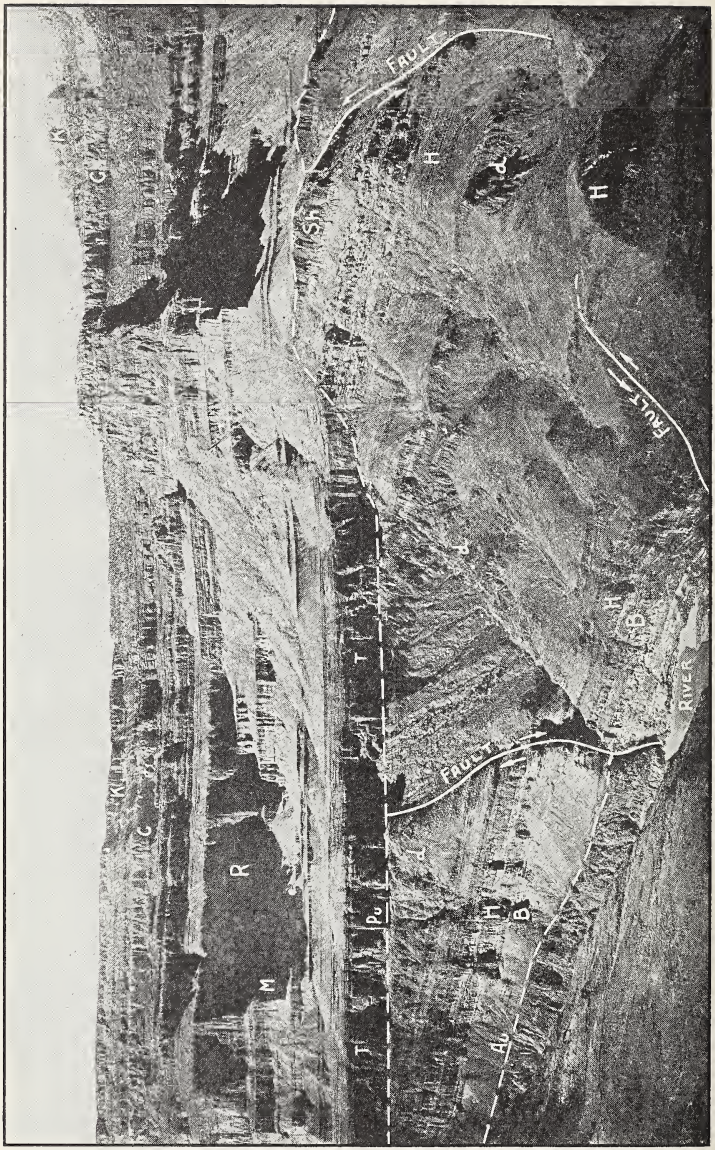


FIGURE 458. THE GRAND CANYON OF THE COLORADO RIVER
(*N. W. Carkhuff, U.S. Geological Survey*)

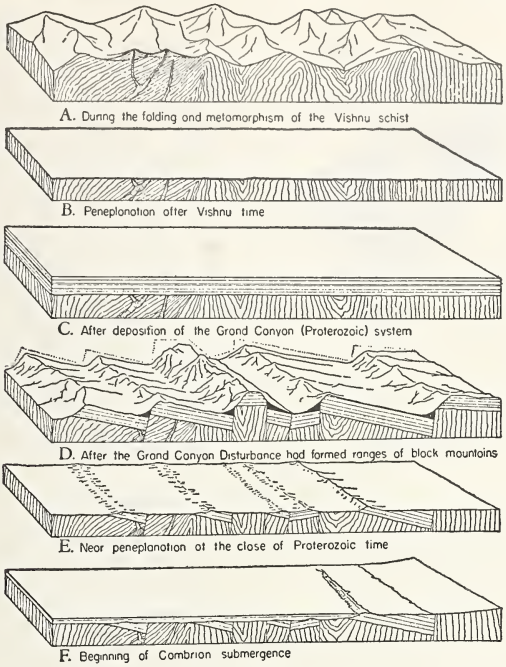

A. During the folding and metamorphism of the Vishnu schist
B. Peneplanation after Vishnu time
C. After deposition of the Grand Canyon (Proterozoic) system
D. After the Grand Canyon Disturbance had formed ranges of block mountains
E. Near peneplanation at the close of Proterozoic time
F. Beginning of Cambrian submergence

FIGURE 459. SIX STAGES IN THE PRE-CAMBRIAN HISTORY OF THE GRAND CANYON REGION

(From Schuchert and Dunbar, "Outlines of Historical Geology," page 63, published by John Wiley and Sons)

rocks. These were deposited after the peneplaned region at the end of Proterozoic time had been again submerged. (Refer to Figure 459.) However, there is not a continuous record of deposition of sedimentary material, because rock correlations definitely indicate the presence of three unconformities. In these rocks are many fossil remains of plants and animals, and the complexity of the forms of life increases with the elevation of the rocks.

The diastrophic movements in this whole region during Paleozoic and Mesozoic time were vertical only as indicated by the horizontal position of these rocks. That the movements were slow is indicated by an entire absence of faults and folds in these younger rocks. Another long period of submergence for this region is indicated by the great depth of rocks of the Mesozoic Era. However, these are not present in the immediate region of the canyon, but can be seen a slight distance north of the Grand Canyon, where an elevation known as Cedar Mountain consists of Mesozoic rocks.

FIGURE 460. AREAS IN NORTH AMERICA WHERE THE PRE-CAMBRIAN ROCKS ARE AT THE SURFACE
(*U.S. Geological Survey*)

A man with a pair of binoculars can stand on the south wall of the canyon and study events which have left their impression on the canyon's north wall: evidence of volcanic activity, the submergence and emergence of this region at least five times, and violent periods of diastrophism which probably accompanied mountain-building on a large scale. As stated before, the Grand Canyon is still a young valley, cut during Cenozoic time. And in the region of the Grand Canyon it is possible to study geological events that are associated with nearly all of geological time.

The Archeozoic Era

The Canadian Shield. The rocks of the Archeozoic Era are also conspicuously exposed throughout large parts of northeastern Canada. (Refer to Figure 460.) Throughout this whole region, referred to as the Canadian Shield, can be seen ancient granites, all that remains of former mountain ranges called the Laurentians formed during the close of the Archeozoic Era. It is, of course, impossible even to surmise the height of this great mountain range when it was reared out of the depths of the earth. In Labrador some peaks still have an elevation of four thousand feet. The Adirondacks, a conspicuous extension of these mountains into New York State, have an elevation of five thousand feet. The rugged character of certain parts of Wisconsin and Minnesota around the western and northern shores of Lake Superior is due to the resistance to erosion of these ancient outcropping Archeozoic granites and diorites. Since they have been subjected in places to processes of erosion during the last four geological eras, it is easy to believe that these mountains when first formed must have been a mighty range.

The Canadian Shield represents a region of great crustal stability. During most of geological time, when the seas were advancing and then retreating from large areas to the east, south, and west, while great geosynclines were being formed and filled with materials which later formed the great mountain systems of the North American continent, the Canadian Shield was relatively stationary, a large island of resistant igneous rocks in a changing continent around it.

The Proterozoic Era

On the edges of the island-like Canadian Shield with its core of Archeozoic rocks can be found Proterozoic rocks. These rocks are prominently exposed through large parts of Ontario in the vicinity of the Great Lakes and in northern Michigan. Lake Superior occupies a great trough where the edge of Proterozoic rocks lies upon the older Archeozoic rocks. From an economic point of view these rocks are of very great significance. The great iron-ore bodies of the Mesabi Range in northern Minnesota, the native copper-bearing formations of the Keweenaw Peninsula in upper Michigan, the rich deposits of nickel, silver, and gold found in Ontario, and many other important ore bodies are found in the Proterozoic rocks on the edge of the Canadian Shield. Similarly, many important mineral deposits in other parts of the world occur in Proterozoic rocks. These deposits are the result of extensive flows of magma which produced a great mountain system, the Killarnies, running in an easterly-by-north direction from northern Wisconsin into Canada. They have since been largely eroded away, though the remains of the granitic batholiths are still conspicuous in northern Wisconsin. (Refer to Figure 461.)

Just when forms of life appeared, of course, is uncertain, but although evidence of life in the Proterozoic rocks is relatively meager, it is known that life existed in the form of marine algae, sponges, and simple forms of life which had no hard parts which would favor preservation.

Reference has already been made to the evidence of extensive crustal movements in the region of the Grand Canyon. Thus, the Hakatai Shale (*H*) and the Bass Limestone (*B*) shown in Figure 458 are Proterozoic in age.

Pre-Cambrian Rocks in the United States. There are a number of very interesting topographical regions in the United States where pre-Cambrian rocks are found. Later, we shall find that the present Appalachians were formed in a great geosyncline which filled with débris from the erosion of former mountains farther east, the so-called Older Appalachian Mountains. The picturesque Highlands of the Hudson, the Blue Ridge Mountains of Virginia, and the Great Smokies of North Carolina are the remnants of a former pre-Cambrian mountain system. The monotony of the great plain east of the Rocky Mountains is broken by the Black Hills of South Dakota.

FIGURE 461. PROTEROZOIC ROCKS IN LAKE SUPERIOR REGION

Here are found the highest mountains east of the Rockies. The Black Hills were formed by sharp upwarping of the earth's crust in this region. The core rocks are of pre-Cambrian age and were pushed up through the Paleozoic and Mesozoic sediments of this region. The younger rocks have long since been eroded away through a large part of the hills. The Black Hills are not only of interest scenically, but also are one of the important mineral-producing regions of this country. The largest gold mine in the United States is the Homestake Mine in South Dakota.

The Paleozoic Era

With the beginning of this era life appeared in great abundance in the seas. Evolutionary processes resulted in many forms of life. The two earliest periods are often called the Age of Marine Invertebrates because of the abundance of trilobites, brachiopods, and shell-bearing mollusks. During Middle Paleozoic time — the Silurian and Devonian Periods — marine vertebrates became common and some gradually adapted themselves to life on land. These were the first amphibians. During the Devonian Period another very significant form of life appeared. Land plants became common. During the Carboniferous Period, the land became covered with a great variety of plants, some of which have persisted down to the present time. Thus, the rocks formed from sediments of this whole era contain numerous index fossils which make the task of correlating them relatively simple. This is one reason why the rock record for this era, which constitutes one-sixth of geological time, is so much more complete than the record of pre-Cambrian time. The era has been divided into six geological periods: Cambrian, Ordovician, Silurian, Devonian, Carboniferous, and Permian — named in order of time from earliest to latest, on the basis of definite orogenetic movements in localized regions throughout the world. The Ordovician Period, for example, was closed by the Taconian disturbance which produced highlands running in a northeasterly direction from eastern Pennsylvania, across New York, to include the present Green Mountains in Vermont.

Many significant events occurred during the Paleozoic Era which later were to affect the economic development of our country. For example, during Silurian time a large part of the interior of the North American continent was beneath the seas. (Refer to Figure 453.) Most of the states of Michigan, Ohio, Indiana, Illinois, Iowa, and large parts of Wisconsin and Oklahoma were then submerged. In these seas were deposited the extensive sediments which have become the limestones now of such great economic importance. These are the Niagaran limestones, which are exposed at Niagara Falls and in many places in Michigan, Ohio, Illinois, and Wisconsin. The Silurian rocks along the length of the Appalachian Mountains also contain extensive deposits of iron ore, especially important near Birmingham, Alabama.

The fluctuations of level of the interior of the North American continent continued during the latter part of the Paleozoic Era, at times being raised slightly above sea level and at other times submerged sufficiently to form large areas of swamp land. The climate was very mild and supported a luxuriant vegetation, such as is found in the tropics today. In time, the swamps became filled with a thick accumulation of vegetable matter, which, when later submerged and subjected to pressure from above, formed our present coal deposits. (Refer to Figure 454.) In some regions this fluctuation of the earth's surface occurred so many times that six to eight different seams of coal can be found separated by shale, limestone, and sandstone. Two-thirds of the world's known reserves are found in the United States and Canada. Scientists have not yet come to complete agreement as to the mode of formation of petroleum and natural gas. However, it is worthy of emphasis that many of the great oil-producing rocks are Paleozoic in age, especially those of the Carboniferous and Ordovician Periods.

The Permian Period, at the end of the Paleozoic Era, was marked by many striking changes. The interior of our continent gradually emerged and the climate became arid, resulting in evaporation of certain arms of the former seas. The dissolved salts, principally sodium chloride and calcium sulfate, then were deposited to form the extensive layers of salt and gypsum now found in Kansas, Oklahoma, Texas, and New Mexico. The great deposits of salt in Michigan and New York resulted from the evaporation of Silurian seas. The southwestern deposits have taken on greater economic significance during recent years because of the discovery of potash in New Mexico. These represent the first extensive deposits of potash — an essential in fertilizers — found in the United States.

The Paleozoic Era was closed by a very significant event: the elevation of the Newer Appalachian Mountains. Reference has already been made to the Older Appalachian Mountains, pre-Cambrian in age, extending from the Hudson Highlands in New York through Pennsylvania and including the Blue Ridge Mountains and the Great Smokies. These are a striking remnant of a once much more conspicuous mountain system in this part of the continent. During most of Paleozoic time, there existed a huge geosyncline just to the west of this mountain system. (Refer to Figure 451.) Whether the crustal forces that elevated the great depth of sediments in this trough into the present Newer Appalachian Mountains came from the southeast or from the northwest is impossible to say; but these forces were great enough to form peaks which may have been five miles in height. The folding throughout the length of this mountain system was intense. There is reason to believe that the crustal shortening in this region may have been as much as one hundred miles. The Appalachian Mountains are now much reduced in altitude as a result of gradational forces. The mountain tops for the most part have been planed off, so there is an absence of

the sharp peaks and precipitous cliffs so common in younger mountain systems like the Rockies.

Mesozoic Era

The rock records of events in this era, which represents one-fourteenth of geological time, are found principally in the western part of our continent. The era opened with a sea creeping down from the north along the present location of the Rocky Mountains. Eventually this sea reached from the Arctic to the present Gulf of Mexico. (Refer to Figure 456 and page 860.) Farther to the west, along the edge of the present continent, there were located smaller geosynclines. One of these is especially significant, for here was formed, during the middle of the Mesozoic Era, the great Sierra Nevada Mountain system of California and Nevada. This period of mountain-building was accompanied by the up-swelling of huge granite batholiths along the core of the present Sierra Nevadas — the largest batholithic mass in the United States. The highest peak in the United States, Mount Whitney, 14,501 feet in elevation, is in the Sierra Nevadas. The Yosemite National Park, famous for its superb mountain scenery, glacier-cut valleys, and high waterfalls, is in the Sierra Nevadas. These igneous rocks have been a rich source of gold. The placer deposits of gold which were responsible for the gold rush to California in 1849, were formed by water washing gold from disintegrated rock into the stream channels.

The Mesozoic Era was closed in a characteristic fashion by (1) general orogenic movements, (2) mountain-building accompanied by volcanism. During the era the Appalachian Mountains, which had been reared at the end of the Paleozoic Era, were almost planed to base level. At the end of Mesozoic time, they were re-elevated perhaps as much as half a mile, and the cycle of erosion started anew. This accounts for the many entrenched meanders and rejuvenated stream systems in the Appalachians. Mountain-building occurred on a grand scale to form the present Rocky Mountains — the so-called Laramide Revolution. Mountains were upthrust from Mexico to Alaska through the overlying Paleozoic and Mesozoic sediments. With the passage of time, however, the Paleozoic and Mesozoic rocks have been largely removed by erosion, exposing the granite core of the Rockies which is pre-Cambrian in origin. One of the notable features of the uplift was the formation of great thrust faults which follow in general the central backbone of the system. There are places where Paleozoic rocks, for example, have slid eastward as much as fifteen miles over younger Mesozoic rocks. Such an overthrust, the Lewis, can be seen in Glacier National Park. The geysers and hot springs of Yellowstone National Park are evidence of former volcanic activity in that region. The subterranean rocks are still hot enough to cause the hot springs and geysers. There is evidence that mountain-building in the Rockies has continued since Mesozoic time and is still in progress. Every great river system which originates

in the Rocky Mountains has had to cut a channel through some mountain range. The channel of the Arkansas River through the Royal Gorge in Colorado was established before the mountains in that vicinity were uplifted. The stream did not cut its present canyon outlet until the whole region began to rise. A few years ago there were a series of several earthquake shocks in the vicinity of Helena, Montana, caused by crustal adjustments along faults in that region.

The Mesozoic Era is the age of reptiles. The amphibians that had ap-

FIGURE 462. NORTH AMERICA DURING THE PLEISTOCENE ICE AGE
(*Courtesy of U.S. Geological Survey*)

peared during late Paleozoic time gradually evolved into reptiles, which flourished during the Mesozoic Era on the land, in the seas, and in the air. In the latter part of this era there were many forms of seed flora, and these forms of life have continued to develop to the present day. Birds appeared during this era. But the most spectacular forms of life were the dinosaurs. These animals increased in such numbers and sizes that they were the rulers of their age and were the most unusual animals the world has ever seen. Some dinosaurs measured from sixty to eighty feet in length and had a body weight as great as forty tons. Not all dinosaurs, however, were huge. Some were carnivorous and lived on the land; some lived a sluggish existence in swamps and were vegetarians; some were alert and rapid in gait; some had a protective armor. They throve over a period of time twice as long as that of the mammals which are dominant today. The dinosaurs had characteristics in common: they reproduced from eggs, were true reptiles, had an unusually low brain capacity, and required a comparatively mild climate for existence. One of the unsolved problems of science is a reason for their sudden disappearance. It is believed that the evolution of the fleeter, more intelligent mammals, together with cooler climates, brought about the relatively rapid extinction of the dinosaurs.

Cenozoic Era

During the Cenozoic Era the North American continent remained emergent, and changes up to the present in the appearance of the continent have in general been due to four geological forces: (1) long continued erosion, (2) volcanism, (3) mountain-building (epeirogeny), and (4) extensive glaciation. Thus, during the early part of the Cenozoic Era, there occurred great fissure eruptions in Washington and Oregon that covered an area of 300,000 square miles with basalt flows in places as thick as five thousand feet. The most significant event, however, of the Cenozoic Era, geologically speaking, was the long period of glaciation that covered most of the northern part of the North American continent. This occurred during the last period of the Cenozoic Era — the Pleistocene (most recent time) — which began about a million years ago.

The surface features of much of the northern half of the North American continent are, in large part, due to the work of the vast ice sheets which extended from Long Island westward through southern Ohio, Indiana, Illinois, Kansas, North Dakota, and Montana to the Pacific Ocean. An era as large as four million square miles was covered with ice, which undoubtedly approached in thickness that of the ice sheet covering Greenland today, which in places is known to be eight thousand feet thick. The mass of accumulated ice flowed out principally from a region east of Hudson Bay, the Labrador Cap, and from a center west of Hudson Bay, the Keewatin Cap, though there were other minor centers of origin. It slowly moved in a southerly direction, and at the time of its greatest advance came

TABLE 69. CALENDAR OF PLEISTOCENE TIME

Period	Name	Years from present estimated
Fourth interglacial	Present	25,000
Fourth glacial	Wisconsin	125,000
Third interglacial	Sangamon	250,000
Third glacial	Illinoisan	350,000
Second interglacial	Yarmouth	650,000
Second glacial	Kansan	750,000
First interglacial	Aftonian	950,000
First glacial	Nebraskan	1,000,000

as far south as the present Missouri and Ohio Rivers. There is evidence indicating that during pre-glacial times the Missouri River flowed into Hudson Bay. But the advance of the ice forced the Missouri to move south, and the present course is approximately where the ice had its farthest advance. Similarly, in the vicinity of Cincinnati, the advance of the ice helped to establish the present course of the Ohio River. During the million years of Pleistocene time, there have been at least four main advances and retreats of the ice sheet. (Refer to Table 69.)

The ice of the first advance, the Nebraskan, came as far south as Kansas City, Missouri. The Kansan came almost as far. The Illinoisan ice originated in Labrador and did not go very far beyond the triangle formed by the Ohio and Mississippi Rivers. The glacial ice of the most recent ice age, the Wisconsin, advanced and retreated more than once, but never went beyond the center of the present states of Indiana, Illinois, and Iowa.

The mantle soil all through the glaciated region, of course, is glacial till. As it moved southward, the great mass of ice ground and crushed the surface of the earth. It thus acted as a huge transporting agent, transferring and depositing the glacial drift which composes the earth's surface throughout the whole glaciated area. The transported materials are of all dimensions, from fine glacial flour to huge boulders weighing as much as six thousand tons. The landscapes of the northern states and those of Canada show the many characteristics of a glaciated region — a soil composed of glacial till entirely different in composition from the bed rock, numerous moraines, eskers, kames, thousands of glacial lakes, outwash plains, and alluvial fans, poor surface drainage, glacial striae in the surface of the bed rock where it had been exposed to moving ice — all the phenomena discussed in Chapter 8.

There is no accepted explanation for the temperature and snow condition which caused the advance and retreat of these continental ice sheets. It is known that the interglacial periods were warm enough to cause the retreat of the ice and long enough to allow plant life to re-establish itself on the new glacial deposits and to permit extensive disintegration of mantle soil by weathering and the formation by growing plants of a fine soil known as *gumbo till*. In many places the successive sheets of glacial drift are sep-

arated by a layer of gumbo till including a layer of buried wood and other vegetation. The mantle from the last Wisconsin advance of the ice is not covered with a layer of fine gumbo till like that of the earlier ice sheets. This is evidence that the retreat of the Wisconsin ice is so recent that not enough time has elapsed to form gumbo till. In other words, the length of time back to the last ice sheet — estimated to be twenty-five thousand years — is considerably shorter than the Sangamon interglacial period which preceded the Wisconsin ice.

The Great Lakes Region. One of the most fascinating series of events during Pleistocene time is the history of the Great Lakes. Lake Superior is the largest fresh water lake in the world, and the Great Lakes region has come to be one of the principal vacation lands of our country. The Great Lakes also play an exceedingly important part in the economic life of the nation. The carving-out of the deep basins to form these vast inland lakes illustrates the power of moving ice. Preceding Paleozoic time, down-warpings

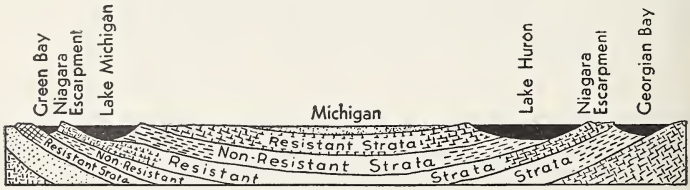


FIGURE 463. THE OUTCROPPING OF THE NIAGARA LIMESTONE

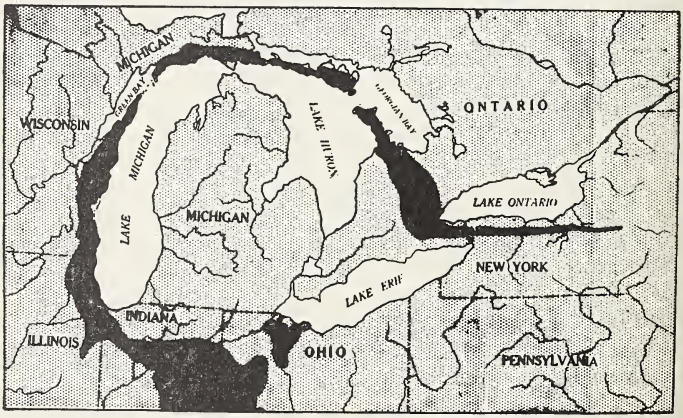


FIGURE 464. THE OUTCROPPING OF THE NIAGARA LIMESTONE FORMS THE RIM OF A HUGE BOWL
(*Courtesy of U.S. Geological Survey*)

in the earth's crust formed the large basin now occupied by Lake Superior. Another deep basin was formed in what is now lower Michigan and parts of Ontario, Ohio, Indiana, and Wisconsin. During Paleozoic time, this huge basin was filled with water from the sea, which remained long enough to form the whole series of sediments known as Cambrian, Ordovician, Silurian, Devonian, and Carboniferous. During Mesozoic and most of Cenozoic time this region was emergent and subject to erosion. With the coming of the thick sheets of glacial ice during the Pleistocene Period, the gouging-out of the lower lakes began. The various layers of rock in the southern Michigan peninsula are shaped like a series of huge bowls. (Refer to Figures 463 and 464.) These alternate layers of sedimentary rocks vary in hardness. The outer edge of the bowl consists of Niagara limestone of Silurian age coming to the surface in a huge circle as shown in Figure 464. This limestone constitutes the rocky ledge of Niagara Falls. Just above the resistant Niagara limestone are comparatively soft Devonian shales. These soft shales originally came to the surface, only to be gouged out by the heavy moving ice sheet to form the huge troughs now occupied by Lakes Michigan, Huron, and Erie. The débris from this Devonian deposit can be found scattered throughout the glacial till immediately to the south of these lakes. It is interesting to note that the rocks immediately below the hard Niagara limestone, which were Ordovician in age, were relatively soft and were likewise gouged out by the ice where they reached the surface to form Green and Georgian Bays and Lake Ontario. (Refer to Figure 463.)

The Great Lakes, of course, did not come into existence until after the final retreat of the ice. The melting ice furnished enormous floods of water which accumulated in front of the ice to flow eventually into the Atlantic or the Gulf of Mexico by a series of drainage outlets which changed as the ice retreated northward. For example, in one of the early stages, water from Lake Maumee, an ancestor of Lake Erie, reached the Ohio River by way of the Wabash River. In this early time, glacial Lake Chicago, the ancestor of Lake Michigan, gave its surplus water to the Mississippi by way of the Illinois River, which must have been a very sizable stream. (Refer to Figure 465.)

When the ice had retreated to the stage shown in Figure 466, ancestral Lake Erie drained to the Atlantic by way of the Hudson River. Lake Chicago continued to use the Illinois River outlet, and the ancestor of Lake Superior, Lake Duluth, drained into the Mississippi by way of the present St. Croix River. With further retreat of the ice, the Great Lakes were for a long time appreciably larger than at present, and all the drainage found its way to the Atlantic by way of the Ottawa River, Mohawk and Hudson Rivers. (Refer to Figure 467.) These northern outlets were so low that the western outlets, Illinois, Rock, Wisconsin, and St. Croix Rivers, ceased to be used. For a part of this interval, the connecting link between Lakes Huron and Erie was abandoned.

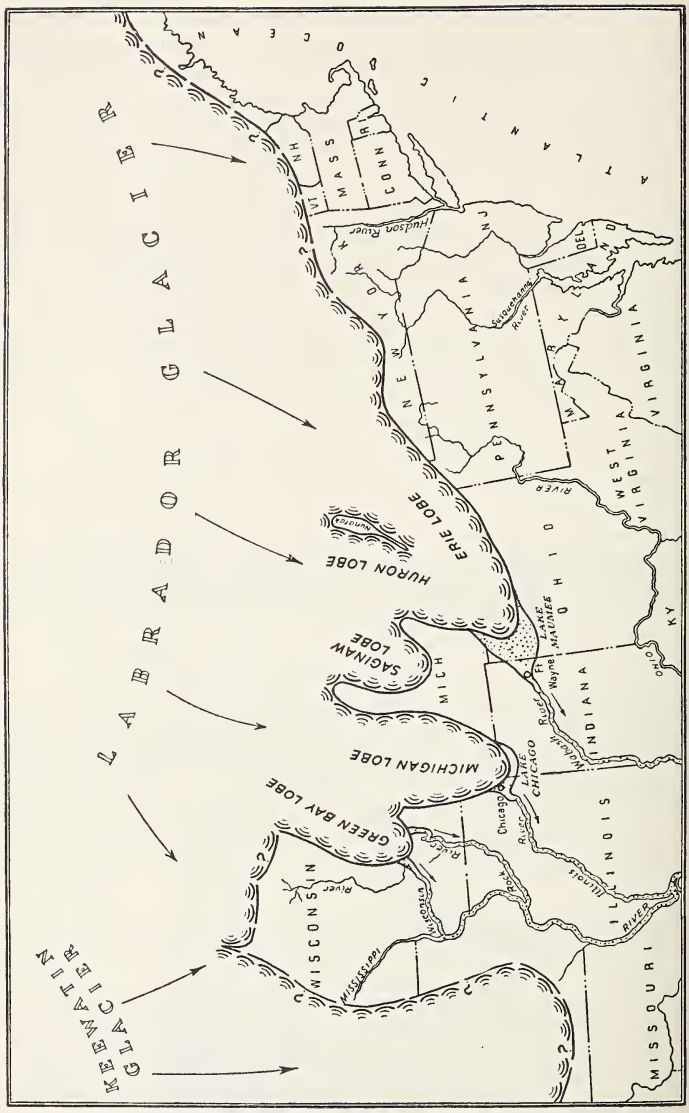


FIGURE 465. THE BEGINNING OF THE GREAT LAKES

(*From "Ne-Saw-Je-Won — A History of the Great Lakes," by Helen M. Martin, by permission of the author and publisher*)

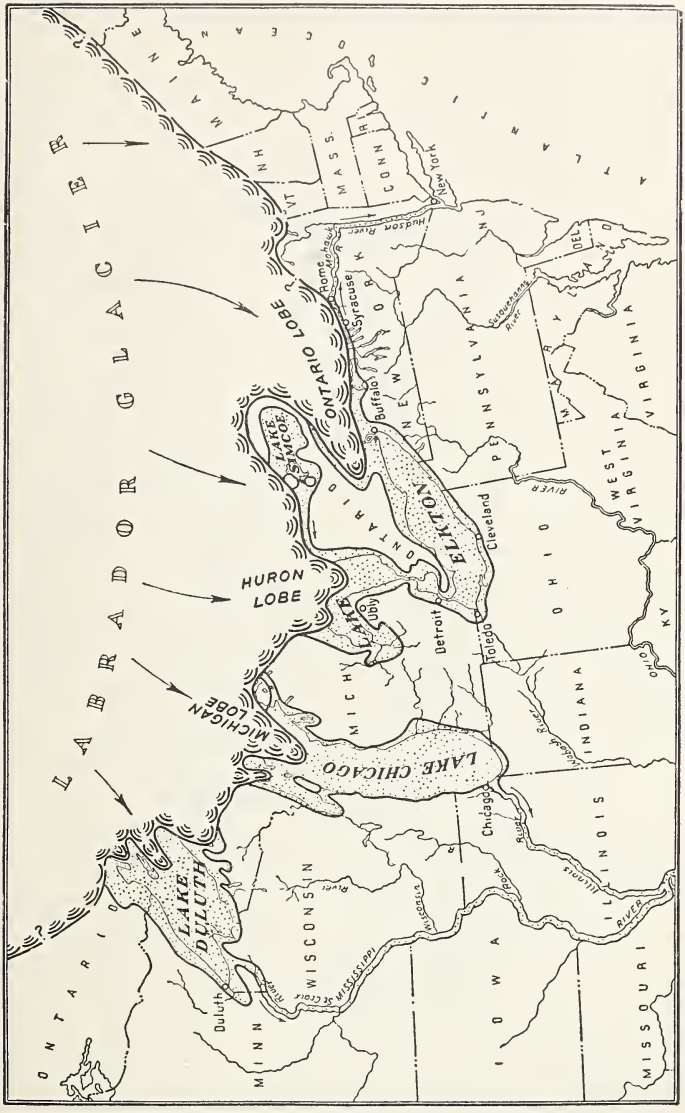


FIGURE 466. THE BEGINNING OF LAKE SUPERIOR

(*From "Ne-Saw-Je-Won — A History of the Great Lakes," by Helen M. Martin, by permission of the author and publisher*)

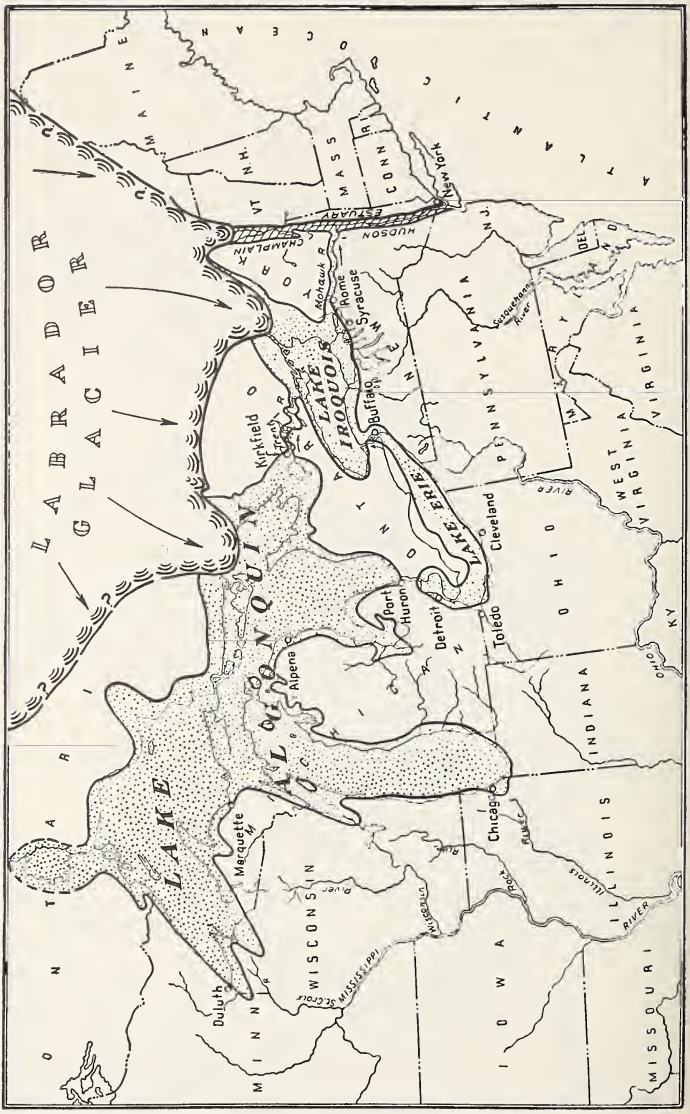


FIGURE 467. THE GREAT LAKES WHEN LARGEST IN EXTENT

(From "Ne-Saw-Je-Won — A History of the Great Lakes," by Helen M. Martin, by permission of the author and publisher)

With the final disappearance of the enormous ice load on the northern part of the continent, the accumulated strains of a million years within the earth's crust were able to exert themselves, and the northern part of the continent itself began to rise. This elevation of the land was sufficient to close the Ottawa River outlet and to reopen the St. Clair River outlet to Lake Erie. This caused a slight decrease in size of the Great Lakes and the establishment of their present drainage by way of the Niagara River into Lake Ontario and into the St. Lawrence.

The history of Niagara Falls is intimately associated with that of the Great Lakes. Here the waters spill over the ledge of Niagara limestone which overlies soft shale and sandstone. The plunging waters undercut the hard limestone, which when deprived of its support falls away block by block. (Refer to Figure 94.) The Falls have retreated a distance of seven miles since they came into existence. They are now retreating at the rate of about four feet a year. Geological events in the history of Niagara Falls can be correlated with the various stages of the Great Lakes. While the lakes were in the stage shown in Figure 467, the only water passing over the Falls came from Lake Erie itself. This was comparatively small in volume. Hence, the canyon cut by the Niagara River during this period is much narrower than that cut immediately before and after that stage, when all the water from the four upper lakes was passing over the Falls.

The Niagara limestone in this region is not horizontal, but gradually plunges into the earth as it approaches Lake Erie at the rate of thirty-five feet per mile. When the Falls, now one hundred and sixty feet in height, will have retreated another two miles, they will be about ninety feet in height. Eventually they must disappear. This will occur when the water in the river below the Falls is at the same level as the Niagara limestone itself. Thus, the apparently permanent Niagara Falls constitute but another brief episode of geological history.

Mountain-Building. All during Cenozoic time, the seas never encroached upon the present North American continent. In many regions the continent was being elevated, especially in the West. The cutting of the Grand Canyon in Arizona occurred during Cenozoic time as that whole region was gradually uplifted. Re-elevation of the Rocky Mountains after a long process of erosion also occurred during this era. As pointed out before, all the great rivers leaving the Rocky Mountains have cut their way across mountain ranges as they were slowly uplifted. The Cascade Mountains, which run parallel to our western coast, were formed during the latter part of the Cenozoic Era. While these mountains were being elevated, volcanism was active throughout this whole region. Mount Shasta (14,161 feet) in northern California and Mount Rainier (14,363 feet) in the Cascades in Washington are extinct volcanoes originally formed during this period. The latest volcanic activity in the region was a minor eruption from Mount Lassen in northern California in 1914.

Changes in Life. There were many significant changes in the forms of plant and animal life during the Cenozoic Era. Mammals which appeared during the latter part of the Mesozoic Era became as dominant as the reptiles had been in the preceding era. With few exceptions mammals were much more agile and intelligent than the ponderous dinosaurs, and adapted themselves to changing environments more readily. The important changes in life forms were (1) the modernization of plants and animals and (2) the development of the present mammalian strains such as the horse, camel, elephant, and the primates, which had their culmination in man. The word Cenozoic means *recent life*. Most present-day forms of life evolved during this era, which is the shortest of the geological eras, representing only about one-thirtieth of geologic time. Trees of modern types — oaks, maples, beeches, palms, pines — appeared. Fishes were likewise modernized. Amphibians were represented by salamanders, toads, and frogs; reptiles included crocodiles and turtles; birds no longer were reptilian in character, but belonged to modern types. Mammals differed from former types of animals in that they were warm-blooded and had milk glands to nourish their young. They penetrated farther into the colder climates of the earth because of an outer covering of fur. In brain capacity mammals greatly exceeded previous forms of animal life.

The Rise of Man

Man's gradual emergence and rise to dominance took place in the Pleistocene Period of the Cenozoic Era. There is general agreement that man evolved from lower forms of primates and that there have been two types of man — *Homo primigenius* and *Homo sapiens*. Man has been in existence for no less than two hundred thousand years. Our knowledge of his development is fragmentary compared to our knowledge of the dinosaur or of the horse. Because of his greater intelligence, as compared with other animals, he was able to avoid sudden death under circumstances favorable to deep burial, which is necessary for the preservation of fossil remains; and it is very probable that at an early date he began the practice of burying his dead. Interment in a shallow grave or above ground, where the processes of weathering are in full operation, does not favor the preservation of fossil remains. These facts account for the comparative rarity of authentic fossil remains of early man. They have also added to the difficulty of tracing, in detail, the story of his rise. The discoveries that are largely responsible for our present knowledge concerning early man can be briefly discussed.

1. *Java Ape-Man.* His are considered to be among the oldest of human remains — *Pithecanthropus erectus* (the ape-man who walked erect). They were discovered in Java in 1891 in a gravel bed. Many extinct mammals occurred in the same bed and indicate early or mid-Pleistocene age. This man stood about five feet six inches in height and had a brain volume of

985 milliliters, as compared with 600 milliliters in the largest apes and 1240 milliliters in the Australian bush savage, the lowest type of living race.

2. *Peking Man.* In 1928, in a cave near Peking, China, were discovered many examples of *Sinanthropus pekingensis.* The brain cavity was a little larger than that of the Java man. Charred animal remains and many crude stone instruments were also found, a fact which indicates that these primitive peoples knew the use of fire and made use of simple weapons and tools. An abundance of extinct mammals in the same deposits date the remains as early or mid-Pleistocene.

3. *Piltdown Man.* Skull fragments found in a gravel bed in Piltdown, England, in 1911–13, indicate that there existed in Europe, during the first interglacial warm period, a race of men somewhat more advanced than *Pithecanthropus erectus* and *Sinanthropus pekingensis.* The brain case had a capacity of 1260 milliliters. There is some indication that this race of men were more progressive than the Neanderthals who succeeded them.

4. *Neanderthal Man.* In 1856, interesting human remains were found in the valley of Neanderthal, near Düsseldorf, Germany. Since then similar skeletons of men, women, and children have been found in caves in Belgium, France, Gibraltar, and Croatia. This race apparently also occupied parts of Asia and Africa. The Neanderthals were short and stocky, about five feet four inches tall, with legs slightly bent at the knees, and with very large heads set forward on the shoulders. The face was probably huge and brutal, yet the brain was about equal in size to that of modern man (1400 to 1600 milliliters). The Neanderthals made fairly good stone and bone implements and ornamental objects, and dressed in furs. They appeared during the third interglacial stage of the Pleistocene age, about two hundred and fifty thousand years ago.

5. *Australopithecus africanus.* On the plateau plains of South Africa there have recently (1936–48) been found many skeletal remains which may prove to have been earliest man, *Australopithecus africanus.* From the evidence that has been uncovered, anthropologists, geologists, and paleontologists seem to concur in the judgment (1949) that *Australopithecus africanus* was closer to man than to the anthropoids, that he had a brain capacity between that of the highest living apes and smallest brained humans, and that he was living about a million years ago during the late Pliocene or very early Pleistocene Periods. If later discoveries substantiate this judgment, it will prove that this early man used fire and hunted even before *Pithecanthropus erectus.*

The foregoing types represent *Homo primigenius.* They were rapidly replaced by the modern species, *Homo sapiens,* about the middle of the last glacial age.

6. *Cro-Magnon Man.* We have said that the entire story of the development of man took place in the Pleistocene Period, a span of probably a million years. (See the geological time-table on page 854.) If all the events

of geological time were relatively crowded into a span of seventy years, then primitive man appeared on the earth eight hours ago, and the first modern man appeared less than a second ago.

Cro-Magnon man, who was modern in appearance, came to western Europe during the last ice age. He walked erect, had a cranial capacity fully equal to that of modern man, and had a high forehead. Many of his ancient cave homes have been found in southern Europe adorned with drawings of animals and scenes of his times. His people were the ancestors of living southern Europeans. As a race they were distinct from *Homo primigenius* and have been called *Homo sapiens*, or discerning man. Their weapons were much improved over those of preceding man. The bow and arrow were common. They developed the art of self-adornment with shell beads, bracelets, and improved clothing. All living human beings are apparently varieties of this single species, *Homo sapiens*.

The rise of man is usually described in terms of his culture as revealed by his weapons and tools, as follows: Paleolithic (Old Stone) Age; Neolithic (New Stone) Age; Bronze Age; Iron Age. The Cro-Magnon people represent the last of the Paleolithic cultures. What we now call civilization began with Neolithic peoples. They were the descendants of the Cro-Magnons. They appeared in large numbers just after the passing of the last ice age some twenty-five thousand years ago. They developed unusual techniques for shaping and polishing articles of stone. They learned to make pottery, weave baskets, spin thread, and make cloth; they constructed homes, domesticated animals, cultivated grains, established villages, and started community life.

There is much evidence of the presence of man in Pleistocene time in North America. In 1925, for example, there was discovered near Folsom, New Mexico, crude stone implements and many arrowheads along with the bones of an extinct species of bison. The arrowheads have a distinctive appearance, and similar ones have been found in many other places in North America. The culture revealed by these stone instruments has come to be referred to as the *Folsom Culture* and was widely distributed over this country as early as about ten thousand years ago. But when the first Europeans reached this country, the culture of the aborigines was still in the stage of the Stone Age.

The neolithic cultures of Asia Minor, Persia, and Egypt were supplanted by the historical cultures of the Bronze Age, which can be traced in Egypt back to about 5000 B.C. and in Chaldea, in the valley of the Tigris and Euphrates, to about 4500 B.C. Copper and bronze could be fabricated into tools and weapons far superior to those made of stone — at the cost of much less labor — and could be used for many articles, such as nails and wire, for which stone is not adaptable at all. Iron came into use in Egypt in about 3000 B.C. With the steady accumulation thenceforth of material means, man could devote himself to exploring the resources of his mind and develop the instruments and collect the data that led to the growth of the sciences.

SUMMARY

1. The Grand Canyon in Arizona and the plateau in which it is incised contain certain rocks deposited in proper sequence from the first four geological eras. The last elevation of this region, which made the canyon possible, occurred during Cenozoic time. Thus, events associated with all five geological eras can be studied in this single locality.
2. The Canadian Shield, largely in northeastern Canada, is a region of great crustal stability, composed principally of pre-Cambrian rocks. The Shield has been relatively stable since the formation of the Laurentian Mountains at the close of the Archeozoic Era.
3. There are a number of conspicuous outcrops of pre-Cambrian rocks in the United States, such as the Adirondacks, the Older Appalachian Mountains, including the Blue Ridge Mountains and the Great Smokies, the Black Hills of South Dakota, and the core of the Rocky Mountains.
4. During the Paleozoic Era, the interior of the North American continent fluctuated above and below sea level many times, and thus formed the extensive deposits of salt, gypsum, and limestone of Silurian and Devonian age, and the coal deposits of the Carboniferous Period.
5. The Paleozoic Period closed with the uplift of the sediments in a great geosyncline which had existed throughout the period to form the Newer Appalachian Mountains.
6. During the Paleozoic Era, forms of life gradually changed from marine invertebrates to marine vertebrates, amphibians, reptiles, and plants.
7. The North American continent was largely emergent during Mesozoic time except for a trough running from Alaska to the Gulf of Mexico. The sediments in this trough were uplifted at the close of the era to form the first Rocky Mountains. The Sierra Nevada Mountains were also formed at the close of the Mesozoic Era as a result of uplift of batholiths. The newer Appalachian Mountains were re-elevated during the latter part of the Mesozoic Era.
8. The Cenozoic Era was marked by (1) vast basalt flows in Oregon and Washington, (2) four extensive periods of glaciation, (3) re-elevation of the Rocky Mountains after the first Rockies had been extensively reduced in elevation by erosion, and (4) re-elevation of the plateau in Arizona which made the Grand Canyon possible.
9. Much of the geography of the upper part of the United States east of the Rockies is the result of the work of ice during four different stages of glaciation — the Nebraskan, Kansan, Illinoisan, and Wisconsin. These ice sheets were responsible for the typical glacial topography in this part of the country, the establishment in their present courses of the Mississippi, Missouri, and Ohio River systems, and the formation of the Great Lakes with the probable exception of Lake Superior.
10. The youngest mountains in North America, the Cascades, were uplifted during the Cenozoic Era. Their uplift was accompanied by considerable volcanism, which has only recently subsided.

11. Proterozoic rocks are usually deeply buried. However, they are exposed in the Grand Canyon and at various places along the southern edge of the Canadian Shield. They are of very great significance from an economic point of view because much of the mineral wealth of the Lake Superior region, iron ore, copper, nickel, silver, gold, platinum, etc., occur in Proterozoic rocks.

12. The rise of man took place during the entire glacial period of Cenozoic time. *Pithecanthropus erectus* (Java man), Piltdown man, and Neanderthal man represent various stages of *Homo primigenius*. The culture of *Homo sapiens* started with Cro-Magnon man about twenty-five thousand years ago.

STUDY EXERCISES

1. In the column at the right, the geologic eras are numbered and the periods are lettered. On the *first* line preceding each item at the left place the *number* which designates the *era*. On the *second* line (if a second line is given), place the *letter* which designates the *period*.

....	Glaciation in Northern Hemisphere
....	Coal deposits formed
....	First horses
....	Piltdown man
....	Oldest sedimentary rocks
....	Laramie Revolution
....	Age of marine invertebrates
....	Deposits of iron in Minnesota and of copper in Michigan
....	First amphibians and land plants
....	Spread of placental mammals
....	Extinction of dinosaurs
....	Appalachian Revolution
....	Dominance of mammals and land floras
....	Shortest era listed
....	Formation of Niagara limestone
....	Earliest rocks studied in geology of Canadian Shield
....	Longest eras listed

1. Archeozoic
2. Proterozoic
3. Paleozoic
   - *A*. Cambrian
   - *B*. Ordovician
   - *C*. Silurian
   - *D*. Devonian
   - *E*. Mississippian
   - *F*. Pennsylvanian
   - *G*. Permian
4. Mesozoic
   - *A*. Triassic
   - *B*. Jurassic
   - *C*. Cretaceous
5. Cenozoic
   - *A*. Eocene
   - *B*. Oligocene
   - *C*. Miocene
   - *D*. Pliocene
   - *E*. Pleistocene

2. Underline the best answer to the following statements:
   (*a*) The Pennsylvania Period is best noted for (*A*, a warm climate with abundant plant life; *B*, the folding and faulting of strata; *C*, saline deposits; *E*, the rise of the dinosaurs).

   (*b*) The era in which fossil forms are unknown is the (*A*, Archeozoic; *B*, Proterozoic; *C*, Paleozoic; *D*, Mesozoic; *E*, Cenozoic).

(*c*) The importance of dinosaurs is due to the fact that (*A*, they had an unlimited geological distribution; *B*, they were found in the last three eras of geologic time; *C*, they are useful as index fossils; *D*, they could withstand changes in climate; *E*, they were rulers of the earth since the earliest times).

(*d*) The presence of a trilobite in a layer of limestone means that (*A*, plants were able to live in water; *B*, a subsidence occurred, followed by an inundation of the land; *C*, mammals must have been present; *D*, the climate was very hot; *E*, the time of deposition was during the Paleozoic Era).

(*e*) The close of each geologic era has (*A*, developed less complex species; *B*, brought about a culmination of all forms of life; *C*, seen the formation of mountains; *D*, been accompanied by a period of submergence; *E*, been marked by extensive glaciation).

(*f*) The remains of early man (*A*, have never been discovered; *B*, are always associated with the remains of dinosaurs; *C*, may be classified in the late Mesozoic Era; *D*, indicate a period in the latter part of the Cenozoic Era; *E*, belong to the Paleozoic Era).

(*g*) The Laurentian Revolution (*A*, produced the oldest mountains; *B*, occurred after the dominance of trilobites; *C*, started the Archeozoic Era; *D*, terminated the Paleozoic Era; *E*, destroyed the fossils of vertebrate forms).

3. Associate by number the period of diastrophism or mountain-building that marked the latter part of each of the following eras:

.... Archeozoic Era	1. Killarney Mountains
.... Proterozoic Era	2. Rocky Mountains — Laramide Revolution
.... Paleozoic Era	3. Appalachian Mountains
.... Mesozoic Era	4. Laurentian Mountains
.... Cenozoic Era	5. The Cascades
	6. The Grand Canyon Revolution

4. What geological circumstance caused the location of the Great Lakes? Briefly outline the general course of the history of the Great Lakes and their relation to the following drainage systems: Wabash, Illinois, Rock, Wisconsin, St. Croix, Mohawk, Hudson, Ottawa, St. Clair, and St. Lawrence Rivers.

5. What were the important changes that occurred in plant and animal life during the Cenozoic Era?

6. Outline briefly the story of the rise of man.

7. In the column at the left are listed localities that represent recognized physiographic regions or places of unusual scenic interest in North America. Identify each by number with the geological era or period in which it originated.

.... Adirondack Mountains	1. Archeozoic
.... Niagara limestone	2. Proterozoic
.... Salt and gypsum deposits in Michigan and New York	3. Pre-Cambrian
	4. Paleozoic

.... Mineral deposits — ores of iron, copper, nickel, and gold — in Minnesota, Michigan, and Ontario
.... Sierra Mountains
.... Cascade Mountains
.... Black Hills
.... Canadian Shield
.... Cutting of the Grand Canyon
.... Rocks found in walls of Grand Canyon
.... Initial elevation of Rocky Mountains
.... Great Smokies
.... Formation of Great Lakes
.... Elevation of newer Appalachian Mountains
.... Formation of coal deposits in an arc from Pennsylvania to Kansas
.... Glaciation of northern United States
.... Evidence of man on North American continent
.... Re-elevation of Appalachian Mountains after a long period of erosion

5. Paleozoic — Silurian
6. Paleozoic — Carboniferous
7. Mesozoic
8. Cenozoic
9. Cenozoic — Pleistocene

FOR FURTHER READING

1. Croneis, C., and W. C. Krumbein, *Down to Earth.*
If time permits read Chapters 33–51 inclusive. Otherwise, read Chapters 33, 35, 37, 38, 41, 42, 46, 47, and 49.

2. Schuchert, Charles, and Clara M. LeVene, *The Earth and Its Rhythms.*
The authors present the science of geology for the general reader. The senior author was for many years professor of paleontology at Yale University. Chapters XX–XXI inclusive consider the history of the earth.

3. Martin, Helen M., *Ne-Saw-Je-Won.* Cleveland: M. D. Harbaugh, 1939.
The story of the Great Lakes and Niagara Falls for the non-technical reader. Many excellent illustrations relate the various stages of these lakes to the position of the retreating ice.

4. Atwood, W. W., *The Physiographic Provinces of North America.* Boston: Ginn and Company, 1940.
This volume presents the principal features of the main physiographic regions of North America. The work of the Ice Age, including a history of the Great Lakes and Niagara Falls, is given on pages 196–224.

5. Mather, Kirtley F., *Old Mother Earth.* Cambridge, Massachusetts: Harvard University Press, 1928.
The author is a professor of geology at Harvard University and one of America's distinguished geologists. This little book presents the principles of geological history in concise, interesting language. The following portions discuss topics treated in this chapter: Chapters III and IV, the story of life; Chapter V, the story of man; Chapters VIII and X, the Ice Age; Chapter IX, the Ice Age in New England; Chapter XV, the making of the Appalachians.

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